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Water Quality Management Program for Puget Sound. Part 1. Management Activities, Data Requirements, and Data Base

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Jones & Stokes Associates, Inc.
1802 136th Place N.E.
Bellevue, WA 98005

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The perception of Puget Sound as a relatively pristine water body has changed in the last few years, and the need for increasingly coordinated and effective management effort is becoming recognized. Jones & Stokes Associates was retained by the U.S. Environmental Protection Agency (EPA) and the Washington State Department of Ecology (WDOE) to evaluate the existing data base and the water quality management tools available to water quality planners and managers. This report identifies and describes the roles of existing water quality management agencies, and identifies data that are needed to evaluate present environmental conditions and predict impacts resulting from water quality regulatory programs and management decisions. The report describes data obtained by previous and ongoing work in view of the data that are needed.

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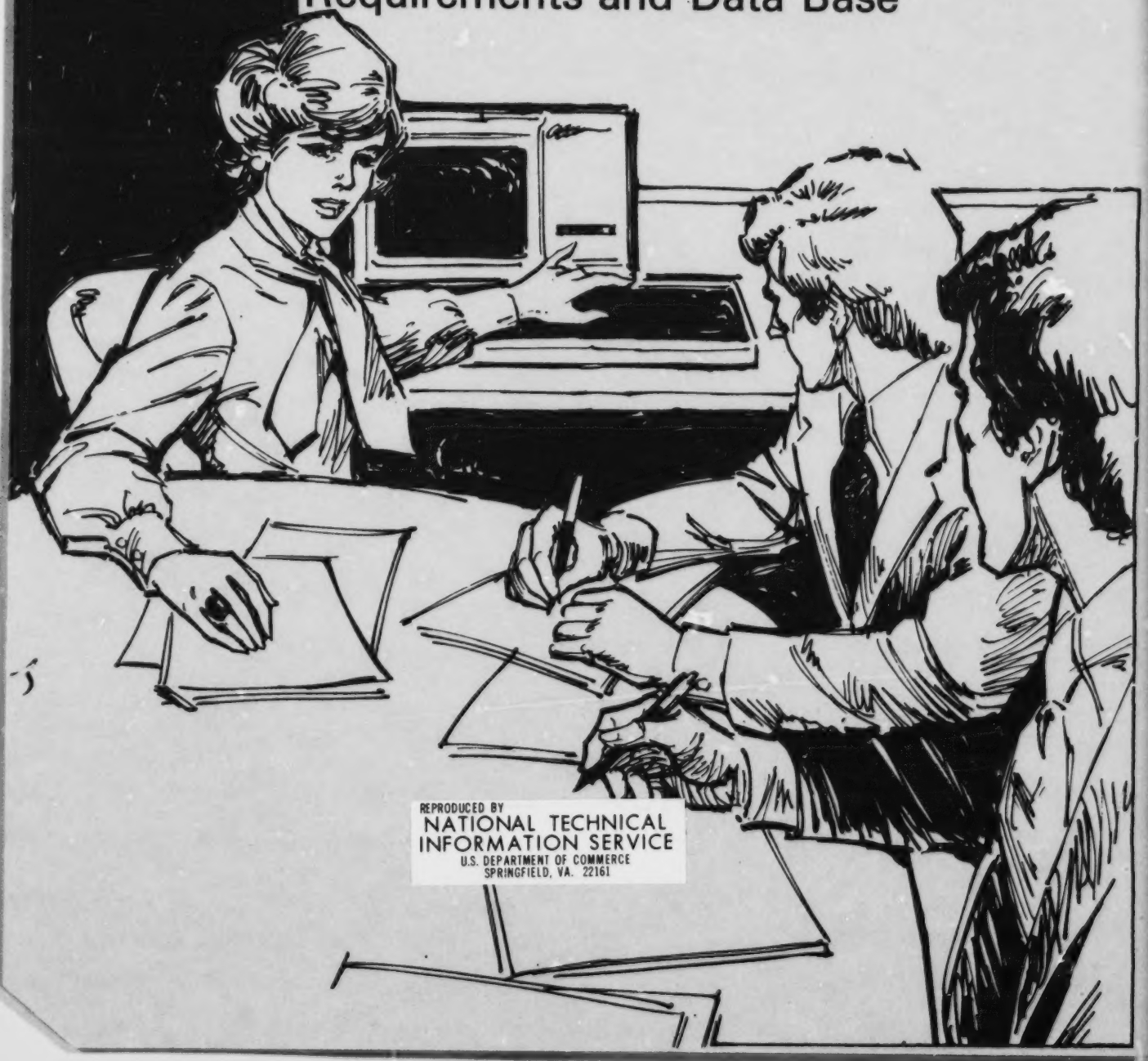

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Prepared for:

U. S. Environmental Protection Agency
Region 10

Prepared by:

Jones & Stokes Associates, Inc.
1802 136th Place NE
Bellevue, WA 98005

and

2321 P Street
Sacramento, CA 95816

and

Tetra Tech, Inc.
1900 116th Avenue NE
Bellevue, WA 98004

August 1, 1983

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EXECUTIVE SUMMARY

Introduction

The perception of Puget Sound as a relatively pristine water body has changed in the last few years, and the need for increasingly coordinated and effective management effort is becoming recognized. Jones & Stokes Associates was retained by the U. S. Environmental Protection Agency (EPA) and the Washington State Department of Ecology (WDOE) to evaluate the existing data base and the water quality management tools available to water quality planners and managers. This report identifies and describes the roles of existing water quality management agencies, and identifies data that are needed to evaluate present environmental conditions and predict impacts resulting from water quality regulatory programs and management decisions. The report describes data obtained by previous and ongoing work in view of the data that are needed.

Management Activities

The responsibility for water quality management of Puget Sound is vested in a number of federal, state, and local agencies (Chapter 2). Although no one agency clearly orchestrates the efforts of all toward a common goal, WDOE plays a major role through administration of state water quality guidelines. It would appear that the only unifying efforts among the agencies are: 1) the common objective of preserving or maintaining a healthy environment, and 2) permit review via the public notice process.

WDOE and the U. S. Army Corps of Engineers (COE) perform major clearinghouse roles at the state and federal permit review level. The permit review process is generally limited by the tendency for each agency to focus attention on specific resource management actions. For example, DSHS is interested in water quality impacts on commercial shellfish beds. Commercial beds do not occur throughout the Sound, and only those DSHS districts with commercial beds may express interest in reviewing NPDES permits or 301(h) waiver applications. In most cases, DSHS review is limited to municipal and domestic dischargers, since major concerns for shellfish have historically been fecal coliform levels and PSP, and not other pollutants. Although not fully understood, but nevertheless of potential major consequence, is the recently affirmed right of tribal governments to influence water quality decisions as they affect salmon and steelhead fisheries.

The environmental legislation having the most widespread impact and greatest relevance to Puget Sound is the Clean Water Act (CWA). The Act and its implementing regulations mandate water quality, effluent limitation, and industrial performance standards; provide grants for point and nonpoint source permit and control programs, and for construction of publicly-owned waste treatment works; and authorize a number of other water quality management activities. EPA retains responsibility for all CWA activities, but delegates implementation to many other federal and state agencies including the COE (dredge and fill permit program); the WDOE (construction grants, water quality standards, nonpoint source planning, NPDES permits); and the U.S. Coast Guard (marine sanitation devices).

Water quality investigation, research, and monitoring efforts are fragmented and generally limited to specific resource management actions of importance to the sponsoring agency. In these three efforts, more than in other management activities, there is little coordination between various agencies. The National Oceanic and Atmospheric Administration (NOAA) has played a major role in water quality investigation and research in Puget Sound through the Marine Ecosystem Analysis (MESA) program. This program was funded by Congress as a line-item appropriation, and has contributed much in the way of research and investigative activity beyond the typically narrow scope of specific resource management objectives.

Data Requirements

Water quality management is normally accomplished by a statutory permit/enforcement program. Ideally, water quality management decisions should be made with full knowledge of the direct and cumulative impacts expected to result from each decision. Knowledgeable decisions require data of several kinds: location and type of pollutant sources; quantity of each potential pollutant discharged; physical, chemical, and biological processes affecting pollutant transport and environmental fate; pollutant distribution and concentrations; toxicity/dose-response data for key species likely to be affected; and synergistic effects of pollutants (Chapter 3). This information will allow a reasonable determination of the maximum loading a system can absorb before an unacceptable biological impact occurs.

Because many ecosystem impacts are difficult to observe or quantify, "unacceptable impact" is most efficiently defined as impairment of a designated beneficial use, or alteration in the ability of certain organisms to survive, grow, and reproduce. These represent key starting points in impact assessment and resource management.

The data base should have two key features: it should contain data which can demonstrate relationships between pollution and effects on beneficial use; and it should be based on

a coordinated multi-disciplinary approach so that data are compatible and consistent from study to study. The available data are reviewed in subsequent chapters of this report (Chapters 4-8).

Available Pollutant Loading Data

Mass loading data provide part of the basis for decision making, but impacts of a discharge (or its removal) can only be determined when the contribution of the discharge is viewed with respect to the cumulative discharges and processes affecting the receiving water mass. Pollution sources may be natural, anthropogenic or, in the case of river input, a mixture of both. The sources are controllable to varying degrees but, until recently, focus has generally been placed on control of anthropogenic point sources. It is important not only to quantify the relative loading of a source, but also to determine the relative degree of control which can be exerted over it so that cleanup efforts can be focused on sources for which it is most cost-effective.

Major sources of pollutant loading include NPDES-permitted discharges, combined sewer overflows, stormwater runoff, atmospheric fallout, dredge-and-fill activities, rivers and streams, advection, and erosion. Available sources of mass loading data and the quality of the data are assessed for the major areas of Puget Sound (Chapter 4). Data are available primarily for point sources, because they are controlled by permits and require discharge monitoring. Conventional and extended conventional water quality parameters comprise the bulk of the available data; with the exception of heavy metals, information on most priority pollutants is often limited to a few analyses. Information on other toxicants which are not considered of sufficient national priority to be listed as EPA priority pollutants (e.g., CBDs) is almost nonexistent.

Loading for nonpoint sources is not documented, partly because nonpoint discharges are not permitted sources, but primarily because their diffuse nature does not easily lend itself to source identification and/or monitoring. Estimates of mass loading for a few pollutants have been made for such nonpoint sources as erosion and atmospheric input, but the estimated inputs vary widely by researcher, depending on the assumptions used. The relative contribution of nonpoint pollution sources to Puget Sound is expected to increase as permit programs bring point source discharges increasingly into compliance with water quality standards and objectives.

In general, mass loading data for Puget Sound are not readily available (Chapter 4). Municipal dischargers have been most extensively studied, but the data are often limited to conventional water quality parameters.

Available Circulation and Dispersion Models

The objectives of the modeling effort for Puget Sound are to identify depositional areas for contaminated solids (fate of solids) and to determine retention time of dissolved pollutants and suspended solids (interbasin transfer, overall circulation patterns, fate of solids). Although major concern is focussed on urbanized embayments because of known or suspected pollution-related impacts on beneficial uses, an overall Puget Sound model is necessary to supply important general information on net circulation, mass transport, and boundary conditions to drive more detailed subarea models.

Fifteen model applications to various portions of Puget Sound were reviewed in the second section of Chapter 5. The purpose of that review was to determine if any existing models of Puget Sound could be adapted by EPA and WDOE as part of their long-range study on developing comprehensive waste management strategies for the Sound.

Major limitations of models that have been or are currently being applied to Puget Sound include:

- Dimensionality - Many of the models use 1-dimensional formulations which represent over-simplified systems. In making water quality management decisions for Puget Sound, knowledge of vertical mixing and transport processes is required. Important lateral concentration gradients are lost in the "average" quantities produced by these models.

- Spatial Resolution - Some of the formulations utilize grids to break up the study area into workable units. Variable values calculated by the model represent average values over the entire grid element. Therefore, use of large elements leads to decreased spatial resolution. Many of the models lack grid flexibility. Detailed information in certain areas (around waste inputs and other areas of interest) and general descriptions in others are required, thus, lack of grid flexibility severely limits the applicability of some models.

- Site-Specificity - Some of the models are site-specific. The assumptions and basic equations used in the models are only applicable to a certain area or water body type.

- Verification and Calibration - Many of the models lack adequate calibration and verification. Before these models can be used to make water quality management decisions, the formulation must be verified and the coefficients must be calibrated for the area being analyzed.

It was concluded that none of the existing models was adequate for this purpose because they are limited by either dimensional or spatial treatment, empirical dependence, or lack of generality. None of the models applied to Puget Sound adequately describes overall circulation patterns, fate of solids, and interbasin transfer on a Sound-wide basis.

It is evident that a model must be developed to provide system-wide information for use in more detailed formulations and to assess the sensitivity of model results to variations of important driving variables and boundary conditions. One option is to modify a model already developed for Puget Sound. Two of the modeling studies were examined in more detail and compared to the present state-of-the-art for estuary hydrodynamic and water quality modeling. These included the model by Jamart and Winter (1978) and the set of models by Water Resources Engineers (1975), which included a steady state fjord hydrodynamic model by Winter (1973). The model developed by Jamart and Winter (1978) employs a unique solution technique which utilizes Fourier transformations. This technique is very efficient and flexible and appears to accurately simulate complex tides and circulation patterns in Puget Sound. The set of models developed by WRE (1975) utilizes a link-node system representation which has been successfully applied in several other areas. This set of models is complex, however, and would require considerable calibration before application to Puget Sound.

A second option is to adapt to Puget Sound a model that has been developed for other areas and comparable conditions. Ideally, the model would be a 3-dimensional representation of the entire system; however, the costs of such a model would be prohibitive, especially for long-term transient simulations. Fortunately, a 2-dimensional, laterally-averaged approximation of the Sound as a whole is justifiable because of the generally narrow and deep nature of Puget Sound. This type of model could be used to describe mass transport, net circulation patterns, and boundary conditions for more detailed models of subareas.

The state-of-the-art model review summarized in the third section of Chapter 5 identified the model by Najarian et al. (1981) as the optimum existing technique for application to Puget Sound as a whole. Modifications that would need to be made for Puget Sound are not major. The model by Sheng and Butler (1982) is recommended for adaption to the Central Basin. It is a 3-dimensional leveled model that has a horizontal coordinate transformation scheme that provides flexibility in grid layout. Other key features of this model include an implicit scheme for the external free-surface mode and a vertical coordinate transformation scheme which provides the same number of continuous layers throught the system. The model should be capable of predicting circulation patterns, mixing processes, solids transport and accumulation, and other water quality variables on a local basis. Specific areas (e.g.,

urbanized embayments) may be considered on a smaller scale basis by adjusting the grid elements and time steps.

A substantial amount of data for use in circulation modeling is available for many physical/chemical parameters in Puget Sound, but it is not in an organized, comprehensive format. Several agencies in the State of Washington have collected field observations. Many of these studies were oriented towards describing specific water quality problems and therefore generated detailed measurements for limited areas. There has been little past effort to combine the data sets to form a comprehensive data base and index for general use. The local agencies most frequently involved with data collection on Puget Sound include: Metro; EPA; WDOE; the University of Washington; and NOAA, including the National Weather Service. Other agencies that collect data on an occasional, site-specific basis are WDF, the U.S. Army COE, and various engineering and oceanographic consulting firms.

Transport and Fate Processes

Transport, fate, and availability of pollutants to organisms are related. Pollutants in the water column may be transported far from their source and are generally most available to pelagic organisms; those deposited in the sediment may remain in one location for long periods and are generally most directly available to benthic organisms. A number of chemical, physical, and biological processes affect pollutant fate and properties. Physical processes include adsorption, dissolution, sedimentation, and resuspension. Chemical processes include speciation, flocculation, chemical precipitation, diffusion, volatilization, photolysis, reduction/oxidation, and hydrolysis/hydration. Biological processes include bioaccumulation, biotransformation, and biodegradation. The chemical structure of each pollutant determines the effects of these processes and the ultimate fate of the pollutant.

A review of literature on properties, fates, sources, and distribution in Puget Sound for the 126 EPA "priority pollutants," petroleum hydrocarbons, polychlorinated dibenzofurans, and particulates reveals numerous data gaps for most of these pollutants. Behavior of many compounds, and even whole groups, is not well understood. Behavior of an entire group often must be inferred from behavior of a single compound or behavior of related compounds because compound-specific data are not available. In addition, reactions are often site-specific and much of the known fate information is based on reactions in a freshwater environment. Interactions in the marine environment in general, and in Puget Sound in particular, are not well understood. Relationships between contaminated sediment, benthic uptake, and organism/ecosystem impact are unclear. Synergistic effects of pollutants on organisms or on

the ecosystem are essentially unknown. Concentrations of pollutants in biota (with the possible exception of metals and PCBs) are not well known.

Certain compounds appear to be of greater concern than others based on their acute and chronic toxicity, their tendency for persistence and bioaccumulation, and the degree and extent of local contamination. Many of the priority pollutants do not appear to be of local concern, while other pollutants not considered as EPA priority pollutants have greater local impact based on their prevalence and properties. Compounds of the most concern appear to be DDT/DDE, PCBs, chlorinated aliphatics (including chlorinated butadienes), polychlorinated dibenzofurans, polycyclic aromatic hydrocarbons (particularly naphthalenes, fluoranthenes, benzo(a)anthracene, benzo(a)pyrene, and possibly pyrene and chrysene) and, to a lesser extent, heavy metals. Others, such as aldrin/dieldrin, are of potential concern, but additional data are needed to determine their status.

Loading of some groups, such as PCBs and chlorinated pesticides, is expected to decrease over time as manufacture and use of many compounds ceases or is greatly reduced. Loading of other pollutants, such as heavy metals, has already been greatly reduced through imposition of NPDES effluent limitations. Loading of groups such as polycyclic hydrocarbons is not likely to decrease naturally, and may increase with increased urbanization.

Water and sediment reflect localized input of contaminants in many areas. In general, the urbanized areas show highest concentrations, although many substances, particularly "nonconventional" pollutants such as organics, are not well documented and their "lack" of local presence is suspected to be due more to lack of sampling then to lack of contamination.

Elliott Bay and the lower Duwamish River show some of the highest levels of As, Cu, Pb, Hg, Zn, DDT/DDE, PCB, MAHs and PAHs. Commencement Bay and its waterways show some of the highest levels of As, Cu, Pb, Hg, Ag, Zn, Sb, chlordane, PCBs, CBDs, MAHs, and PAHs. Sinclair Inlet shows some of the highest levels of As, Cu, Hg, Ag, Zn, PCBs, and PAHs. High levels of As and Zn have been noted in Budd Inlet as well, and high levels of Hg have been noted in Bellingham Bay. More extensive sampling of sediments in areas such as Bellingham Bay, Everett Harbor, and Hood Canal might show additional high concentrations of these substances. Over 1,000 organic compounds have been identified from urban embayment sediments, and many still have not been identified. Of these, the polycyclic aromatic hydrocarbons (PAHs) are probably of greatest overall concern because of their diversity, levels of concentration, and potential effects. Studies of these compounds in Puget Sound sediments are limited, and areas of greatest concentration can only be surmised at this point, but it is probably safe to

assume that all urban embayments will show some areas of high, localized concentrations, although the compounds may vary.

Available Data on Biological Effects

Fish

Investigations of the ecology of fish communities in Puget Sound have failed to indicate any substantial adverse impacts of municipal waste discharge on species composition, abundance, or diversity. The available data suggest that in the vicinity of Seattle's West Point sewage outfall, there may be some increased abundances of demersal fishes, and there may be relatively minor alterations in species composition of this community which might be caused by the discharge of sewage effluent. Other differences noted at West Point may be attributed to natural habitat differences rather than to sewage discharge. Studies of the ecology of fish communities in the vicinity of other municipal sewage effluent discharges on Puget Sound are inappropriate for demonstrating effects on fish communities.

Extensive studies conducted in the vicinity of several pulp and paper mills in the mid-1960s demonstrated that the mills were often located adjacent to important nursery areas for both anadromous and marine fish species. In addition, it was apparent that the effluent from these mills was often highly toxic to juvenile fishes, and that the ecological implications of these industrial discharges were therefore potentially very important. Since that time, there have been dramatic reductions in the pollutant discharges from these mills, as they were forced to either institute more advanced treatment measures or shift to other processing methods. Follow-up studies have been conducted in Port Gardner as part of the ECOBAM program, but the results have not yet been released.

The Puget Sound region has two heavily-industrialized urban estuaries: the Duwamish River-Elliott Bay system in Seattle, and the Puyallup River-Commencement Bay system in Tacoma. Both are known to have received large quantities of toxic chemicals over the years, and several studies have attempted to examine the effects that industrialization and chemical contamination of these areas have had on the resident fish communities. Detailed comparisons have not been made, however, between the fish communities of the urban, industrialized estuaries and those of undeveloped, nonindustrialized estuaries (e.g., the Nisqually River Delta), so it is difficult to describe accurately how the fish communities of the urban estuaries may have been altered by industrial activities. Malins et al. (1982a) found that the abundance of some fish species (as indicated by the catch per unit effort) was negatively correlated with the distributions of some toxicants in the sediments of these estuaries. While such correlations are suggestive of cause-and-effect relationships

between the fish distributions and the concentrations of chemical contaminants, far more detailed studies will have to be conducted before it is known what factors ultimately influence the abundance of these and other fish species.

It is of interest to know what effect the disposal of dredge spoils (especially chemically-contaminated dredge spoils from the urban estuaries) might have on fish populations, but the limited studies conducted to date do not permit definitive conclusions. Studies of such relationships must be relatively extensive in order to discriminate natural population fluctuations from dredge spoil disposal effects, and such extensive sampling has not been conducted at any disposal area in Puget Sound.

Laboratory toxicity bioassays with fishes have been conducted using sediments and sewage treatment plant effluents. Effluent bioassays can be used as an indication of relative toxicity under controlled conditions. Toxic constituent concentrations can also be measured throughout the exposure period. Their major limitation is that they do not enable an assessment of the interactive or cumulative effects of the numerous pollutant sources that exist in many industrialized areas of Puget Sound. Existing data indicate that lethal toxicity of municipal effluent is a function of sewage treatment technology and periodic releases of "slugs" of toxicants. Studies on toxic effects of dredge spoil activities are limited by site-specific conditions.

In situ bioassays with fishes have been used in the Puget Sound area near pulp and paper mill effluents and near dredging operations. The results of such studies can be confounded by the lack of available water quality information at the exposure site and high mortalities in control cages. Such studies are valuable, however, in assessing relative changes in toxicity (i.e., water quality), either in a spatial or temporal context. For example, previous *in situ* studies have demonstrated that acute toxicity can occur in salmonids exposed to pulp and paper mill discharges. Continuing use of this technique could potentially serve to examine the change in ambient toxicity associated with improvements in effluent treatment.

While there have been numerous investigations of the concentrations of metals in the tissues of various fish species from Puget Sound, there have been few, if any, definitive results which conclusively demonstrate the accumulation of metals in these tissues in excess of "normal" or "background" concentrations. Although virtually all of the metals examined exist in detectable concentrations in the tissues of the fishes, the general conclusion is that it is not known whether the reported concentrations are in excess of background concentrations for fishes in relatively "unpolluted" waters. Several reasons can be cited for this lack of conclusive evidence of the existence or absence of significant bioaccumulation of metals.

First and foremost is the fact that none of the studies to date has included sufficient numbers of replicate samples to allow statistical analysis of the data. In the absence of sufficient replicates, it is impossible to judge whether an apparent difference in the tissue concentrations of a given metal in the fish from two different areas is statistically significant or whether observed differences simply reflect natural variation. Studies completed to date have utilized a wide variety of fish species, and virtually nothing is known about species-specific susceptibility to the bioaccumulation of metals. The available evidence suggestive of bioaccumulation is primarily for demersal fish species, while pelagic fish species are apparently less prone to bioaccumulate metals. Many of the past studies have often suffered from the lack of fish samples collected from an appropriate control area. While it is often difficult to select a control area having characteristics similar to those in a polluted area except for the presence of chemical contaminants, past studies have often included no control area at all or an area whose "unpolluted" status is either assumed or poorly documented.

Available data on the concentrations of PCBs in fishes of Puget Sound (and similarly for most other organic contaminants) suffer from many of the same problems found with data on the concentrations of metals in fishes (e.g., lack of adequate replication, differences in fish species analyzed, lack of appropriate controls). Nevertheless, these data are more suggestive of significant bioaccumulation because the differences in the concentrations of these compounds between fish in known polluted areas and those in background or control areas are much larger than are the usual differences in metals concentrations between two such areas. Whereas metals concentrations often only differ by two- or three-fold between fish in polluted urban areas and those in presumed control areas, the concentrations of PCBs in fish from two such areas often differ by one or two (or even more) orders of magnitude. The available evidence suggests that accumulation of PCBs is most pronounced in demersal fishes (e.g., English sole, rock sole, sculpins) inhabiting urban estuaries (e.g., Commencement Bay, Elliott Bay, Duwamish River) known to have sediments contaminated with high concentrations of these compounds.

There have been very few studies of the concentrations of organic contaminants other than PCBs in the tissues of fishes from Puget Sound. The limited data available suggest that chlorinated butadienes are found in consistently high concentrations in fish from the Hylebos Waterway in Tacoma, but nowhere else, while chlorinated hydrocarbon pesticides and hexachlorobenzene are found in high concentrations in fish not only from the Hylebos Waterway but also from the Duwamish River and the Seattle Waterfront. Polynuclear aromatic hydrocarbons are generally present only in low concentrations in the livers of fishes from all areas of Puget Sound. This reflects the fact that fish are apparently able to metabolize these compounds.

They are, however, present in slightly higher concentrations in fish from Elliott and Commencement Bays. Correlations between the body burdens of virtually all of the organic chemical contaminants and known sources of these compounds are best for the demersal fishes, and not well developed for semi-pelagic or pelagic species.

The mechanisms of bioaccumulation of organic contaminants are not known at this time. It is not known, for instance, whether the primary pathway into the bodies of the fishes is via ingestion of contaminated prey organisms, uptake through the gills and skin or contact with contaminated sediments. There are a limited amount of data that suggest uptake of PCB does not result from exposure to PCB in the water column. The consequences to fishes, if any, that result from accumulation of these substances are also largely unknown.

Numerous studies of pathological conditions among fishes of Puget Sound have revealed several consistent relationships: the conditions often occur in higher prevalence in areas known to be contaminated by a diversity of chemicals, they appear to affect demersal fish species (e.g., flounder and sole) more often than pelagic fish species (e.g., salmon), and their etiology is largely unknown. Fin erosion disease, while not confined to polluted, urban areas, is more prevalent in such areas, suggesting that the condition is in some way caused by exposure to chemical contaminants. While certain evidence from lab exposures and field studies suggests that chemical contamination may be involved in the initiation of this disease, it is entirely possible that a combination of factors (e.g., chemical contamination, mechanical injury, physical factors) act in concert to bring about fin erosion. The distribution of skin tumor prevalence basically follows that of fin erosion; it is more common in areas with chemically-contaminated sediments than in less polluted areas. However, the association of skin tumors with contaminated environments is even more tenuous than the incidence of fin erosion. While the consequences of fin erosion for the individual fish are unknown, there are indications that skin tumors may be eventually fatal to fishes. It has been established, for instance, that the prevalence of tumor-bearing fish decreases with increasing age of the fish, suggesting that tumor-bearing fish disappear from the populations more rapidly than do normal fish. As is the case with fin erosion, it is entirely possible that multiple factors act either independently or synergistically to cause skin tumors.

Hepatomas and other liver abnormalities clearly occur much more frequently in demersal fishes from industrialized, urban estuaries than in less polluted areas of Puget Sound. Circumstantial evidence once again points to chemical contaminants as an important factor in the induction of these conditions.

For the other pathological abnormalities observed among fishes of Puget Sound, there have been relatively few detailed

studies. Since these conditions occur at relatively low frequencies, much more extensive studies would be required to demonstrate any relationship between the distribution of these conditions and the distribution of known areas of chemical contamination.

Whereas there is a good evidence of an association between the occurrence of pathological conditions in demersal fishes and the sites of intense industrial activity, the prevalence of fish disease does not appear markedly higher in the vicinity of large municipal sewage discharges, such as West Point, than in other similar areas without municipal sewage discharges. One possible hypothesis is that these pathological conditions are a function of some factor present in industrial wastes, but absent, or in considerably lower concentration, in municipal sewage effluents. An alternative hypothesis is that municipal sewage discharges are deliberately sited in areas of high flushing where fine suspended particulates are unlikely to settle, and therefore, initiation of toxic conditions is minimized.

It is a relatively straightforward proposition to sample the fishes in polluted and unpolluted areas of Puget Sound, to examine them for a variety of pathological conditions, and to assign percent prevalences of each condition to the respective areas. Given sufficiently large sample sizes, it is possible to demonstrate that statistically-significant differences occur in the prevalences of these conditions in the various areas, and that some of the conditions are most prevalent in the most contaminated areas.

Beyond simply documenting the existence of fish disease in various areas of Puget Sound, there have been relatively few attempts to investigate the causes of the observed pathological conditions. There are similarities between certain of these conditions occurring naturally in the fishes of Puget Sound and those induced in laboratory animals by exposure to a variety of chemical pollutants. There are interesting statistical correlations between the distribution of fish with certain of these conditions and the distribution of groups of chemical contaminants. This does not imply cause-and-effect, however, since it is still not known whether one chemical acting independently, or several acting synergistically, or even an as yet unmeasured chemical which happened to be correlated with the other chemicals, was/were the causal factor(s). Measurements of the concentrations of chemical contaminants in the tissues of fish with specific pathological conditions, as well as in the tissues of healthy fishes, have been performed on too few specimens to provide statistically-significant correlations which might indicate what chemicals cause these conditions.

Laboratory experiments designed to attempt to induce certain pathological conditions in fish by exposing them to chemically-contaminated sediments or by injecting them with extracts of those sediments have failed to reproduce those

conditions observed in natural fishes from contaminated areas. The prospect of testing individually all or even a large fraction of the total array of chemical contaminants known to occur in such sediments is overwhelming, while testing the likelihood of synergistic effects among all of the possible combinations of those chemicals is virtually impossible.

Benthic Macroinvertebrates

Investigations of the ecology of benthic communities near pollutant sources have documented responses associated with changes in community structure and with changes in abundances of selected species. Although only one study examined the effects of dredged material disposal on benthos, the immediate effects and subsequent recovery were well documented. Studies of benthic communities in many industrialized embayments and nonindustrial areas in Puget Sound have not resulted in definitive conclusions on the possible modifications of benthic communities in areas of known sediment contamination.

Several studies of benthic macroinvertebrate assemblages near sewage discharges in Puget Sound have been conducted in support of applications for waivers from secondary treatment requirements. Biological effects at the largest single sewage discharge in Puget Sound (West Point) were associated with reduced total abundances and reduced abundances of some taxa in areas near the discharge. Although the causative agent(s) for the observed effects is unclear, recent evaluation of the infaunal data suggests that the local subtidal benthic communities may be responding to contaminated particulates. Comprehensive studies of intertidal floral and faunal assemblages near West Point and other areas of central Puget Sound receiving sewage discharges indicated that the only apparent effect was associated with modification of algal communities near West Point.

No definitive effects of smaller municipal sewage discharges have been documented at other sites in Puget Sound. These results may be due in part to the limited nature (e.g., few samples) of most of the studies. However, many of the smaller municipal discharges are located in erosional environments where high currents prevent sewage solids from accumulating near the outfalls. Thus, potential effects on the benthos are minimal at such sites.

Effects of pulp and paper mill discharges on subtidal benthos have been documented at several Puget Sound sites. The effects ranged from almost complete absence of macrofaunal benthos in inner harbor areas near the discharges to moderate changes in community structure at sites farther from the discharges. The reviewed studies were conducted during periods when pulp and paper mill discharges were considerably greater than at present, or when the magnitude of those discharges was just being reduced. Thus, the actual degree of recovery that

may have occurred is unknown. Data from European waters (Pearson and Rosenberg 1978) indicate that recovery is possible in as little as 3 years, and present a potentially useful indicator of environmental stress on the benthic community.

Several studies have been conducted to determine the toxicity of Puget Sound sediments to benthic organisms. Amphipods have been the major test organisms used; however, tests have also been conducted on oligochaetes, polychaetes, several bivalve mollusc species, and decapod crustaceans. The results have indicated that sediments in the industrialized areas of Puget Sound are toxic to many of the species tested. Specific results are dependent upon test species used and exposure apparatus/procedure. In one case (Swartz et al. 1982) the bioassay results were related to observed distributional characteristics of infaunal species (i.e., absence of amphipods from areas with toxic sediments). Perhaps the most interesting outcome of these bioassay results is the observation that sediment toxicity is very localized, suggesting that sediment contamination is also very patchy. More than one investigator has noted that sediment samples taken in the same general area show noticeably different toxic effects. These data suggest that sediment toxicity bioassays should incorporate a sampling design that accounts for highly localized distribution of contaminants.

The primary limitation of the sediment bioassays is the general absence of two kinds of information:

- Biological characteristics of indigenous benthic communities at the site of sample collection.
- Chemical analyses of sediment contaminants.

The previously conducted bioassays have served primarily to identify areas of potentially toxic sediments in the Puget Sound region. The causative agent(s) or the actual effects on indigenous organisms are presently unknown.

Surveys of bioaccumulation of metals in benthic organisms indicate that higher tissue levels of several metals are found near Seattle. There is also evidence of elevated levels of some metals in mussels in Commencement Bay. However, the studies of bioaccumulation of metals in invertebrates are limited by the same factors that were identified in studies on fishes. Of special note are the rather inconclusive results obtained in studies of arsenic accumulation in the vicinity of a major point source of arsenic in Commencement Bay.

Shrimp, clams, and mussels have been shown to accumulate PCBs in areas of PCB contamination. The degree of PCB bioaccumulation is generally related to the degree of sediment contamination.

Only one study was reviewed that examined pathological conditions in invertebrate organisms. Although the results are somewhat inconclusive due to small sample sizes, there was an indication of increased prevalences of lesions in crabs and shrimp from industrialized areas.

Plankton

Studies of phytoplankton ecology have been conducted near sewage discharges, pulp and paper mill discharges and dredge spoil disposal sites. The most comprehensive studies were oriented toward effects of the West Point sewage discharge on primary production. Overall, the only indication of effects on phytoplankton at West Point are associated with the possibility of stimulation of primary production during periods of nutrient depletion.

Studies of meroplankton (e.g., ichthyoplankton) have been extremely limited and cause-and-effect pollution-related studies of zooplankton have apparently not been conducted in Puget Sound.

Because of the naturally high levels of spatial and temporal variability of plankton assemblages, studies sufficient to define cause-and-effect relationships must generally be rather intensive. Large numbers of samples collected at relatively short time intervals are generally necessary to define pollutant effects. Because of study design limitations and because of the low probability of pollutant or nutrient impacts in the main basins of Puget Sound, cause-and-effect relationships for plankton have not been established.

Bioaccumulation studies of plankton have concentrated on uptake of PCBs in zooplankton. Tissue levels of PCBs have been shown to be dependent upon PCB concentrations in the water and lipid content of the organisms. Studies of metal accumulation in Puget Sound zooplankton are largely inconclusive.

Toxicity tests using plankton have concentrated on Pacific oyster larvae. Limited studies have also been conducted on the toxic effects of PCBs on phytoplankton and zooplankton. The oyster larvae bioassay has been used extensively in testing a variety of pollutants using mortality and abnormal development as toxic responses. The bioassays have been used to test larval responses to dredge spoils; pulp mill, smelter, and oil refinery effluents; and dinoflagellate blooms. In general, oyster larvae were more sensitive to toxicants than other Puget Sound biota. Thus, the bioassay provides an important mechanism for establishing safe effluent levels for most Puget Sound organisms.

Conclusions From Available Biological Effects Studies

For the Puget Sound region, the most intensively studied biological effects include organism abundances, toxicity, and bioaccumulation. Fishes have received the greatest study effort; however, considerable work has also been conducted on assessment of toxicity using benthos and plankton. There is little or no information concerning potential biological effects on behavior and reproduction.

The reviewed studies have produced several kinds of information that characterize biological effects, including identification of effects (or absence thereof) on indigenous biota; identification of tissue contamination and abnormal pathological conditions in organisms inhabiting industrialized areas; and identification of probable relationships between contaminated sediments and bioaccumulation, disease, and mortality of Puget Sound organisms.

Although effects on biota (e.g., fin erosion, bioaccumulation) have been implicated in field studies, information on quantitative cause-and-effect relationships is lacking in many areas. For example, apparent effects of the West Point sewage discharge have been detected in local infaunal communities. However, the available information is not adequate to characterize the cause(s) of the observed effects or to establish a quantitative cause-and-effect relationship. Information required for such determinations would include measurements of solids deposition rates or sediment contaminant concentrations at the same sites used for infaunal benthos sampling. With those kinds of data, changes in biological response variables (e.g., abundance of species A) could be quantitatively related to causative agents.

Studies of bioaccumulation have demonstrated that various contaminants (e.g., PCBs, CBDs, and several metals) occur in elevated concentrations in Puget Sound biota. However, information on uptake routes, intertrophic transfer, and depuration rates is generally lacking. Moreover, quantitative relationships between sediment or water concentrations and organism tissue levels also are not available.

As in the case of some heavy metals, it is known that PCBs are toxic to many organisms at low concentrations. Data from the literature indicate that PCBs are taken up from sediments and from the water column, and that PCBs induce some of the pathological conditions observed in urbanized embayments of Puget Sound. These latter observations, although obtained in laboratory conditions, are evidence that PCBs may be causing some of the observed pathologies of fishes. This does not, however, constitute evidence that PCBs are the only causal agent for fish abnormalities in Puget Sound.

Overall, past studies in the Puget Sound region have served to identify the nature and location of biological effects.

Although some cause-and-effect relationships have been established or are suggested by available data, additional studies will be required for the determination of quantitative relationships that are useful for predictive purposes.

Monitoring Programs

Existing long range monitoring programs are limited in number and analytical coverage. As a result, it is difficult to use data from these programs to evaluate environmental conditions, establish trends, and predict impacts of water quality management decisions. Private studies often tend to provide more in-depth data, but only for localized areas and over short durations, which makes trend determinations difficult. However, because of their greater detail, short-term studies may ultimately provide data of greater value for specific uses such as problem identification than that provided by routine water quality monitoring. The value of the various monitoring programs and special studies could be enhanced if the comparability of the data was strengthened through an integrated quality assurance program. There is a strong need for a well-defined set of goals for short and long-term monitoring activities to guide current and future programs.

Summary

The available data do not clearly link specific pollutants to specific adverse impacts on beneficial uses. Given the scientific complexities involved, development of specific cause-effect relationships may not be possible in many instances. Nevertheless, the weight of circumstantial evidence indicates a positive association between areas of high contaminant discharge and changes in or adverse impacts on beneficial uses in these areas. The water quality manager is faced on the one hand with a significant degree of scientific uncertainty regarding cause and effect and on the other hand with identifiable problems and the need to initiate rememdial activities. The challenge is to use most effectively the available information while developing an improved data base for use in future decisions.

Two approaches to the use of existing information can be of use to water quality managers at the present. The first involves comparisons of information from similar problem areas. For example, in the absence of a documented cause-and-effect relationships between specific pollutants and pathological abnormalities observed in fish populations, it may be valid to look for characteristics common to those localities. In reviewing contaminants in the environments of

so-called diseased fish in areas such as Elliott Bay, Commencement Bay, coastal Southern California, and Chesapeake Bay, the most obvious similarity is the presence of a number of chlorinated hydrocarbons, especially PCBs, pesticides, and compounds typically associated with wastewater chlorination, in the sediments. Only limited data on the occurrence of these contaminants in fish tissue is available and no consistent pattern between contaminant levels and disesase incidence has been established. It is possible that a more detailed comparative analysis of conditions in these areas, coupled with theoretical information on biological activity and toxicity, will provide guidance to the water quality manager on appropriate regulatory targets.

A second approach involves the identification of pollution gradients within the Sound to identify problem areas and then to develop correlations between pollution conditions and observed effects on biota or beneficial uses in those areas. For some of the urban bays within the Sound this type of data base and correlation are available and additional work is underway to strengthen the comparisons with baseline conditions. While these types of correlation are not definitive cause-effect relationships they can provide guidance to water quality managers in making educated regulatory decisions within localized areas.

Waste management decisions ultimately come down to establishing priorities among sources or classes of sources and implementing appropriate control programs. At the present time, mass loading data for many of the contaminants of concern are very limited in most geographic areas within the Sound. Possible exceptions are Elliott Bay and Commencement Bay and even these data on loading from certain types of sources are minimal. Examples of the kind of problems encountered with the existing data base include lack of significant data on combined sewer overflows, limited analytical coverage in some areas, and limited data on seasonal variations in loading. A significant effort is needed to strengthen the mass loading data base in priority problem areas. In the interim the existing data base, and appropriate data from other areas, needs to be thoroughly evaluated and where possible extrapolated to Puget Sound. This information, coupled with the analyses of environmental data described above, could aid in sharpening the focus of water quality management decisions required in the near term.

Existing circulation modeling efforts are generally useful to the water quality manager to predict dilution rates and dilution zones of the outfall plume. Some models may help estimate the flushing rate for a localized water body, but all

of these models describe dilution of the wastewater and, therefore, describe the likely transport of dissolved pollutants and pollutants adsorbed to suspended particulates that remain in the water column during the dilution period.

Conclusion

Water quality managers have the regulatory tools to respond to and to prevent and abate pollution once there is sufficient evidence to show reasonable cause that a discharge/activity has an adverse effect on beneficial uses or resources. Although a comprehensive water quality management structure is operating, it is not fully integrated and coordinated in respect to the acquisition and use of data and information.

With the expection of effluent analyses done as part of the 301(h) waiver applications for municipal discharges and as NPDES permit compliance monitoring on behalf of a few selected industrial discharges, there are very few data to describe sources and mass loading of priority pollutants. Although the EPA priority pollutant list is a reasonable starting point for identifying pollutants requiring special consideration in Puget Sound, many of the compounds have not been found in the Puget Sound environment, and a few other compounds known to be toxic but not on the list have been found.

Knowledge about the dispersion and fate of pollutants is based primarily on theoretical considerations, simplifying models, and limited empirical data identifying where certain toxicants have accumulated in the environment. The build-up of potentially toxic substances in bottom sedients is documented, particularly in the Central Basin. The data indicate highly localized distribution of contaminants in the sediments.

The toxic characteristics of priority pollutants are well documented (otherwise they would not have been designated as an EPA priority pollutant). Pathogenic conditions observed in some demersal fish, especially English sole and starry flounder, are inferentially associated with bottom sediments containing abnormally high concentrations of toxicants. Generally, there are few data that link indirect effects on biota with specific pollutants, much less with sources of pollutants.

Water quality monitoring in Puget Sound is done primarily by WDOE, NPDES permittees, USGS, and DSHS. In some cases, the objectives of monitoring are not given or poorly defined. Although conventional pollutants are usually not included, and consistency is lacking in the coordination of sampling and analytical procedures to permit maximum uses of all data.

Despite the limitations in the existing data, thorough evaluations of this information can provide significant guidance to water quality managers.

Chapter 1

INTRODUCTION

Statement of Problem

A cursory review of many documents about the environment of Puget Sound reveals that many authors refer to Puget Sound as a treasured resource of great beauty and diverse beneficial uses. If not explicitly stated, it has been implied that one underlying factor influencing the wealth of beneficial uses is minimal evidence of pollution. The belief that Puget Sound is a relatively unpolluted water body has changed in the last few years. Since 1978, investigators have called for serious reconsideration of the presumed purity of Puget Sound. Investigations (e.g., Pierce et al. 1978; Malins et al. 1982a) reveal that certain pollutants occur in relatively high concentrations in the sediments and fauna of some urbanized embayments. It also has been noted that some bottomfish collected from urban embayments display histopathological or grossly visible pathological abnormalities.

Recent events further challenge the presumption that Puget Sound is a clean water body. The Washington Department of Fisheries (WDF) recorded mass mortalities on herring spawning areas at Quarter- master Harbor, Port Madison and Port Gambel (Dahlgren pers. comm.). The Washington Department of Ecology (WDOE) has noted increased incidences of decertification of shellfish beds because of adverse water quality and paralytic shellfish poisoning caused by red tide (Monn pers. comm.). Recent studies of Commencement Bay (e.g., Riley et al. 1981; Dexter et al. 1981) contributed to the listing of Commencement Bay as a priority site in need of Superfund clean-up money. The public has shown a greater concern over symptoms of environmental degradation during the past decade.

The public and scientific community impose on Puget Sound beneficial uses defined by their collective knowledge of the Sound. Federal and state governmental agencies have missions to manage certain resources and maintain beneficial uses for present and future users. A generic diagram of the resource management process is shown in Figure 1-1. To accomplish their stated missions, management agencies have developed tools (e.g. permit issuance, periodic permit review, monitoring, enforcement, and public education) which require large amounts of data and knowledge if they are to be effectively implemented. These environmental data are typically supplied by past and ongoing studies. Data gaps must be filled by new studies. Management agencies often contribute data and influence the course of studies by defining environmental data needs. Critical to the

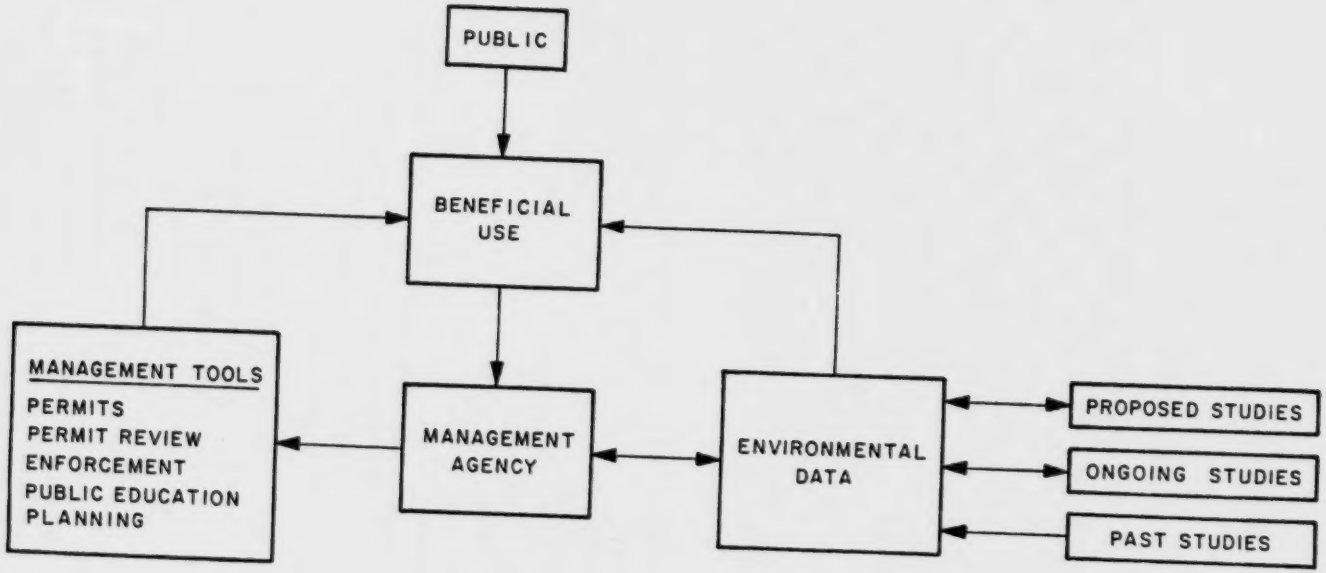


Figure 1-1. Relationship Between Beneficial Uses of Resource, Management Agencies, Management Tools, and Environmental Data

success of resource management is the use of feedback loops between management agencies, resource users, and the technical community.

Direct evidence and symptoms of environmental degradation suggest that the public may be losing existing or potential beneficial uses of the Sound. As a result of technical findings and concerns for resource impacts, public and private discussion of this issue has focused on the need for reevaluating the direction of Puget Sound water quality management.

Objective of Report

Jones & Stokes Associates was retained by the U. S. Environmental Protection Agency (EPA), in association with WDOE, to evaluate the existing environmental data base and water quality management tools used by water quality managers of Puget Sound. The objectives of this work effort are to:

- Identify and describe the roles of various agencies participating in water quality management.
- Describe the data needed to evaluate environmental conditions and predict impacts on the environment resulting from the composite of regulatory programs and decisions implemented by these agencies.
- Describe the existing data in view of the water quality management needs of EPA and WDOE.
- Identify missing data that are needed to evaluate environmental conditions and predict impacts on the environment resulting from the composite of regulatory programs and decisions implemented by these agencies.

This "state-of-the-art" report will provide the initial framework for a second report which in turn will recommend new studies and changes in ongoing or proposed studies that will provide the environmental data required to meet management objectives.

Description of Study Area

Puget Sound is an inland sea extending between the Olympic Peninsula on the west and the Cascade Range on the east. It is linked to the Pacific Ocean by the Strait of Juan de Fuca and the Strait of Georgia (Figure 1-2). The San Juan Islands are located southeast of Vancouver Island in the area where the Straits of Juan de Fuca and Georgia meet. The border between the United States and Canada travels through the Strait of Juan de Fuca, Haro Strait and, for a short distance, through the Strait of Georgia before turning eastward along the 49th parallel.

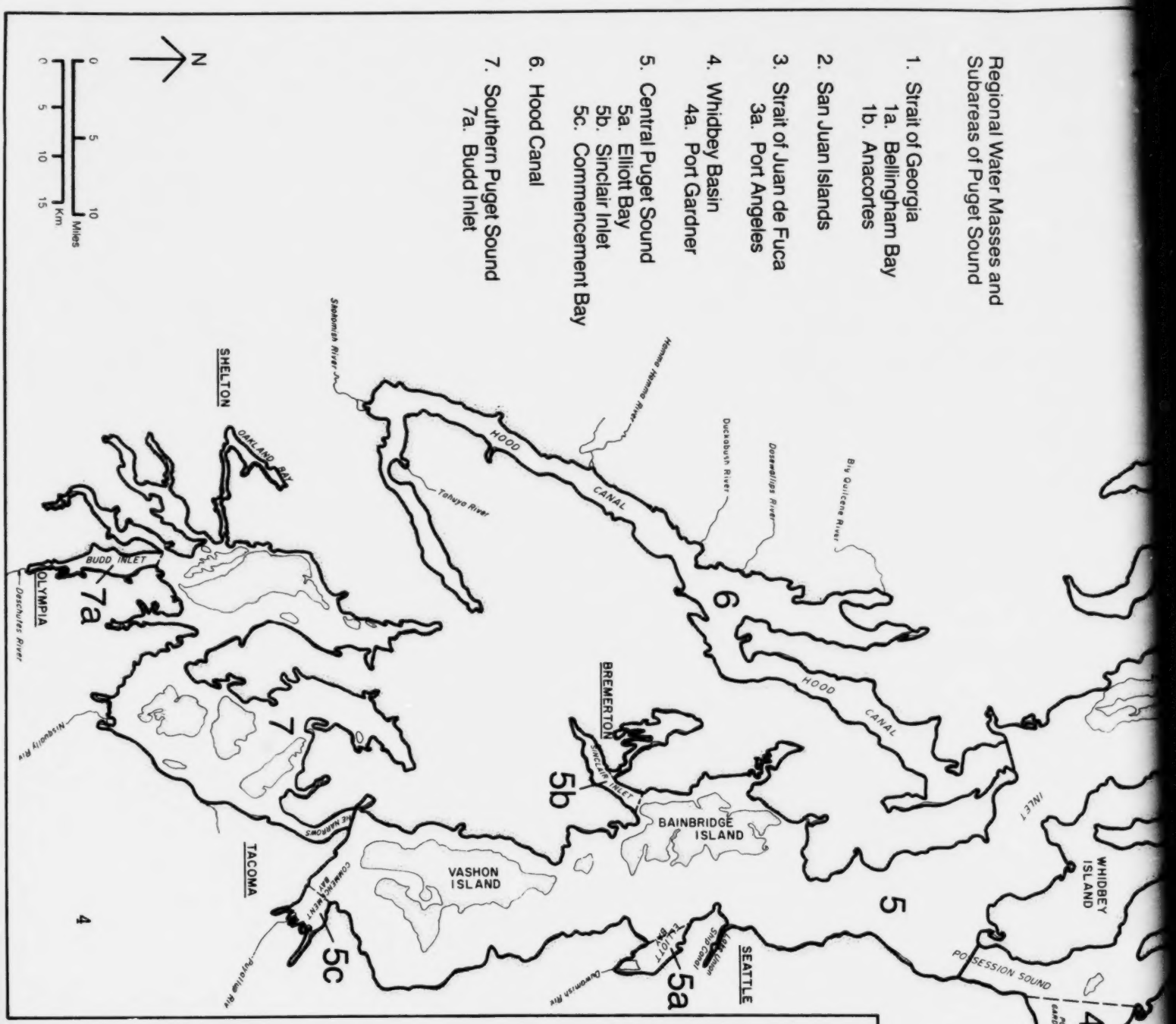
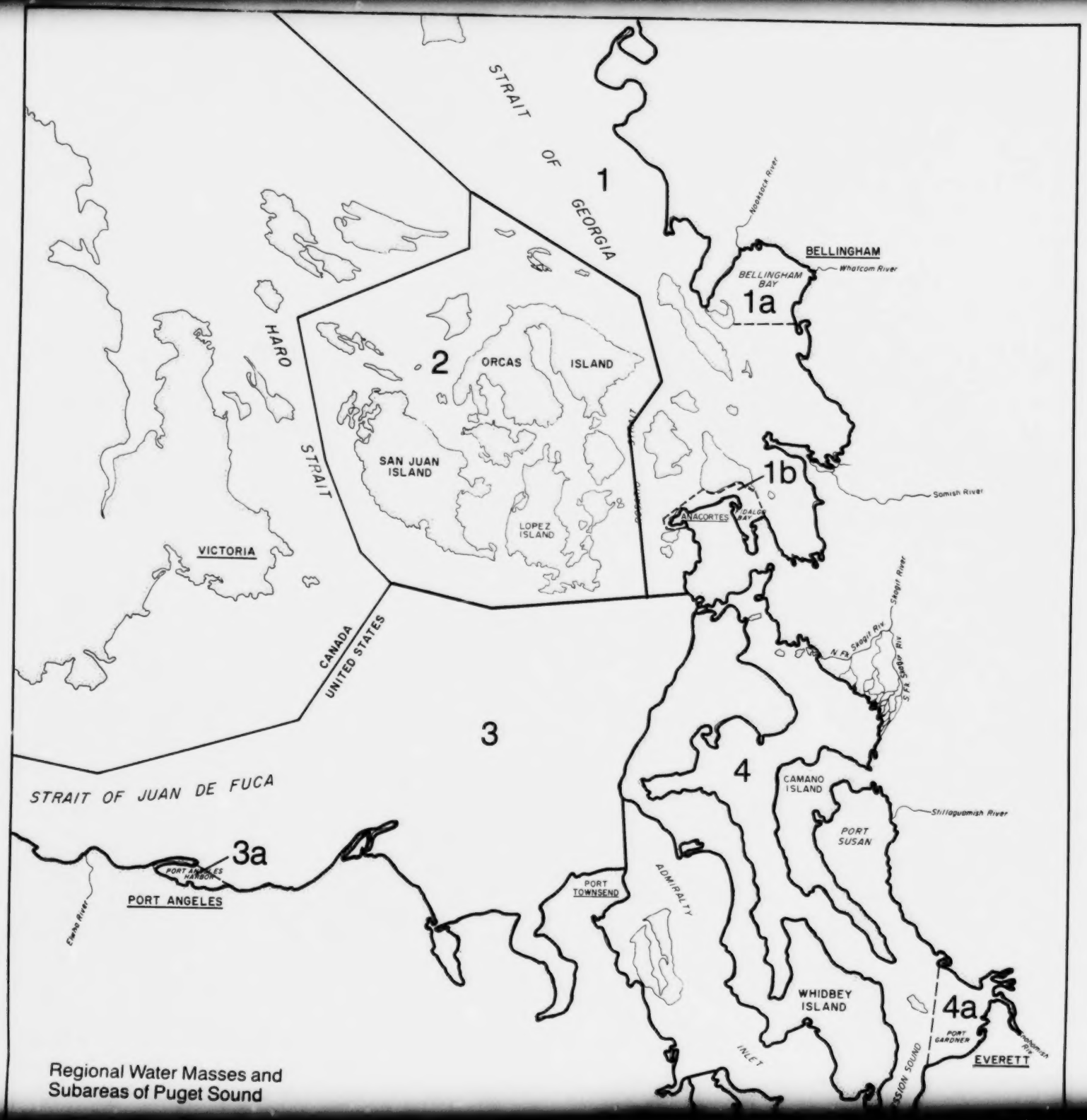


Figure 1-2. Map of the Study Area Showing Division of Area into Regional Water Masses and Subareas of Concern



Regional Water Masses and Subareas of Puget Sound

Puget Sound extends southward from the Strait of Juan de Fuca for over 160 kilometers (100 miles). It is comprised of a series of basins 180-240 meters (600-800 feet) deep, separated by shallower sills 30-60 meters (100-200 feet) deep. This fjord-like feature is further expressed in the generally steep slopes from the shoreline to basin floors.

The Sound and the Straits, within the territorial seas of the United States, enclose 6,500 square kilometers (2,500 square miles) of protected or semi-protected water and about 3,700 kilometers (2,300 miles) of shoreline. The mildly cool climate, abundant natural resources, and protected harbors served as strong attractants for early colonization and development. The urban areas around Puget Sound are centers of commerce and trade between the northwestern part of the continental United States, Alaska, and the Far East. Timber from the surrounding watersheds and fisheries in Puget Sound are major natural resources contributing to commercial activity along the shorelines.

Because of its bathymetry and geographic configuration, Puget Sound can be subdivided into several fairly distinct water bodies (Figure 1-2). The main basin of Puget Sound (Central Basin) extends from Admiralty Inlet to the north and Tacoma Narrows to the south. Elliott Bay and Commencement Bay on the east shore serve as natural harbors for the Cities of Seattle and Tacoma, respectively. Most of the east shore is heavily populated or industrialized. The west shore is more rural, although a major naval shipyard on Sinclair Inlet provides a major economic base for the City of Bremerton.

Southern Puget Sound extends south from the Narrows as relatively shallow inlets. The lack of natural deepwater harbors has discouraged the industrialization of this area. Extensive mudflats are exposed at low tide, and the area supports a rich and diverse assemblage of marine invertebrates and water-associated birds.

Hood Canal is a narrow, shallow finger of Puget Sound extending southwesterly from the southern part of Admiralty Inlet. Its shallow depths and confined outlet encourage warmer water temperatures and, therefore, water-contact recreational activity. Although supporting less extensive tidal areas than southern Puget Sound, Hood Canal supports rich shellfish populations and mariculture activities in shallow water areas. Development is primarily rural or residential, with the exception of a naval submarine base and associated support activities at Bangor.

Whidbey Basin is functionally a part of Puget Sound because Whidbey Island effectively isolates this watermass from Rosario Strait and the Strait of Juan de Fuca, leaving Possession Sound as the major connection to oceanic influence. Whidbey Basin is heavily influenced by freshwater flow from the Skagit,

Stillaguamish, and Snohomish Rivers. The Skagit River is the major source of freshwater flow into Puget Sound, and forms a large delta and shallow-water alluvial fan at the north end of the Whidbey Basin. Development in the Whidbey Basin is primarily rural or residential, with the exception of deepwater areas near Everett. The northern part of the Whidbey Basin is occupied by a rich and diverse assemblage of waterfowl, marine, and estuarine species.

The area covered by this report includes all of Puget Sound, including the Whidbey Basin, and major urbanized areas on the American shoreline from the Strait of Juan de Fuca through the San Juan Islands to Bellingham. The latter areas include Port Angeles Harbor, the Anacortes area, and Bellingham Bay (Figure 1-2).

Beneficial Uses

Beneficial uses relate both to societal needs and ecological processes. Beneficial uses are important to water quality management, because they provide goals on which to establish water quality programs and associated environmental standards. The pursuit of definable goals and supporting standards serves the future through maintenance of identifiable beneficial uses. At the same time, maintenance of beneficial uses should maintain the integrity of the ecosystem supporting the beneficial use. For example, when water quality standards are established and maintained at levels enabling optimum production of a beneficial use (such as anadromous salmon), other organisms (e.g., prey species, habitat species) benefit because these must be kept at levels of productivity appropriate to maintaining the salmon population. This does not indicate, however, that the ecosystem is not changed and possibly diminished in some manner by management directed toward the beneficial uses. The greatest difficulties in resource management and regulatory activity occur when two or more beneficial uses are in conflict. A case in point would be the controversy between the expansion of sea otter populations and shellfish harvesting in the coastal waters of central California.

Beneficial uses are generally one of two types: those that are legally permitted and widely acknowledged as acceptable uses (e.g., navigation, fisheries, mariculture, recreation, species habitat), and those that are legally permitted and tolerated because of cost/benefit factors associated with alternative activities. Examples of the latter type of beneficial use are log storage and wastewater discharge.

Although wastewater discharge in the Sound can economically benefit society in general, it can, if not managed properly, cause serious reductions in the achievement of other social and economic benefits (i.e., beneficial uses) derived from the Sound. Wastewater discharge is not considered by the EPA or the

WDOE to be a protected beneficial use of the Sound, and its continuance depends on wastewater treatment and the removal of pollutants that are not acceptably assimilated into the ecosystem.

Summary

The perception of Puget Sound as a relatively pristine water body has changed in the last few years, and the need for increasingly coordinated and effective management effort is becoming recognized. Jones & Stokes Associates has been retained by the EPA and the WDOE to evaluate the existing data base and the water quality management tools available to water quality planners and managers. This report identifies and describes the roles of existing water quality management agencies, and identifies data that are needed to allow evaluation of present environmental conditions and prediction of impacts resulting from water quality regulatory programs and management decisions. The report describes data obtained by previous and ongoing work in view of the data that are needed to evaluate current conditions of the environment and make management decisions.

Chapter 2

WATER QUALITY MANAGEMENT IN PUGET SOUND

Agency Responsibilities and Programs

Water quality management in Puget Sound is the responsibility of several federal, state, and local agencies, as established by federal, state, and local laws. Although agency responsibilities as established by law often reflect considerable overlap, agencies have operating mechanisms that tend to narrowly focus on water quality issues pertinent to the central mission of each agency. Water quality management is generally accomplished through a permitting process, and is generally orchestrated through provisions of the National Environmental Policy Act (42 USC 4321 et seq.) and implementing regulations (40 CFR Parts 1500-1508), and the State Environmental Policy Act (RCW 43.21C) and implementing regulations (WAC 197-10). As a result, the regulatory framework for making water quality management decisions is comprised of a web of mandated or delegated authority displaying surprisingly little duplication of effort and an acceptable degree of coordination during project permit issuance or review. However, there is rarely a coordinated effort to approach water quality management on any scale larger than a case-by-case (permit-by-permit) basis. Technical studies that provide data to the permitting processes typically occur on a case-by-case basis with minimal coordination between agencies, often resulting in duplication of effort or incompatible sets of data.

In the interests of clarity, the terms "investigation", "research", and "monitoring" are not used interchangeably. Research as used here indicates a scientific study developing new techniques or involving hypothesis testing by the use of experimental manipulation of conditions and established controls. This definition does not necessarily minimize the scientific value of investigative studies, such as the systematic sampling of levels of pollutants in various substances. Monitoring is considered here as a special type of study in which efforts are made to detect changes or effects over a period of time occurring after the onset of certain activities.

The following discussion briefly summarizes the applicable roles of various federal, state, or local agencies that address water quality issues pertinent to Puget Sound. The discussion does not present in detail the many caveats or implementing

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regulations that would be included in a thorough analysis of agency roles; rather, an effort is made to provide an overview of how these agencies individually or collectively influence water quality management decisions relative to Puget Sound.

Federal Agencies

Governmental structures normally have separate legislative, executive, and judicial functions engaged in a constitutional system of checks and balances. With the exception of compliance with the National Environmental Policy Act (NEPA), there often is not a legal requirement that agencies or programs performing these separate functions be consistent with one another. The agencies listed below operate generally within a set of established legal requirements and negotiated agreements of understanding that provide for coordinated effort. It is a system in which the activities of each agency are constrained by the mandated activities of the others and by NEPA-authorized regulations that require all federal actions to be consistent with the nation's environmental quality objectives.

U. S. ENVIRONMENTAL PROTECTION AGENCY

An objective of the Federal Water Pollution Control Act (FWPCA) (33 USC 1251 et seq.) as amended in 1972, was to restore and maintain the chemical, physical, and biological integrity of the nation's waters. One national goal is to achieve water quality that protects and supports populations of fish and wildlife and provides recreational opportunities in and on the water. The regulatory framework for implementing the goals and policies spelled out in the FWPCA is the responsibility of the EPA.

The FWPCA was renewed and amended as the Clean Water Act (CWA) of 1977. Some sections of the CWA establish either grants, water quality standards, or permit programs that are intended to control or abate water pollution. Major sections of the CWA pertinent to water quality management in Puget Sound are:

Section 106 - Grants for state pollution control programs

Section 201 - Grants for construction of treatment works

Section 208 - Grants for areawide waste treatment management

Section 301 - Effluent limitation standards

Section 303 - State water quality standards and implementation plans

Section 306 - National standards of performance (by industry)

Section 307 - Toxic and pretreatment effluent standards (priority pollutant)

Section 311 - Oil and hazardous substance liability

Section 312 - Marine sanitation devices

Section 316 - Thermal discharges

Section 401 - State certification of federal projects or permit activities

Section 402 - National Pollutant Discharge Elimination System (NPDES) permit

Section 403 - Ocean discharge criteria

Section 404 - Permits for dredged or fill material

Section 510 - State authority

Under these and other sections of the CWA, EPA is authorized to encourage or carry out a variety of investigative, research, monitoring, regulatory, and enforcement programs.

EPA retains responsibility for all CWA activities, but may delegate certain activities to either the state or to other federal agencies. Many CWA programs have been delegated by EPA to the State of Washington; however, EPA continues to:

- Develop guidelines for Best Available Technology (BAT) economically achievable for toxic pollutants, and Best Conventional Technology (BCT) for conventional pollutants.
- Develop categorical pretreatment standards.
- Evaluate Section 301(h) waiver applications and implement the 301(h) waiver program.
- Administer NPDES permits for federal facilities and facilities within Indian reservations.

In addition to monitoring the CWA, EPA is responsible for implementing the goals and policies spelled out in several other federal laws that interact to protect the environment. The Resource Conservation and Recovery Act (RCRA) establishes national policies and programs for solid waste management in general, and for hazardous waste management in particular (42

USC 3251 et seq.). Subtitle C of RCRA establishes a program for comprehensive "cradle-to-grave" regulation of hazardous wastes. The Comprehensive Environmental Response, Compensation, and Liability Act (also known as the Superfund program), is a funding source to clean up areas contaminated by hazardous chemicals when private clean-up funds are unavailable or inadequate (42 USC 9601 et seq. and 26 USC 4611 et seq.). The disposal of certain hazardous wastes is also regulated by the Toxic Substances Control Act (15 USC 2601 et seq.) and the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA) (7 USC 136 et seq.). Other federal laws (e.g., Clean Air Act [42 USC 1857 et seq.], Coastal Zone Management Act [16 USC 1451 et seq.]) also affect water quality management of Puget Sound indirectly through land use planning and control of point and nonpoint pollution sources.

U. S. Army Corps of Engineers

Under the terms of the CWA and a Memorandum of Understanding (MOU) with EPA, the U. S. Army Corps of Engineers (COE) is assigned responsibility for the Section 404 (dredged or fill material) permit system. This responsibility is an extension of the COE permit responsibility under Section 10 of the Rivers and Harbors Act of 1899 (33 USC 403). The COE permit program under Section 404 covers the discharge of dredged or fill material in a broader definition of waters of the United States, whereas, the permit program under Section 10 covered dredging, excavating, filling or other modifying activities in waters specifically defined as navigable waters.

The COE publishes public notices of all pending permit applications. These notices are sent to governmental agencies, environmental groups, and other parties requesting to be included on the mailing list. Through this public notice process, the COE may receive input from several federal, state, and local agencies and private interests regarding permit conditions and approval or denial. Under the authority of Section 401 of the CWA, the WDOE determines whether the permitted activity would meet state water quality standards. The input to the COE is a function of how often comments are provided to the COE, and the thoroughness of the agencies' review process. EPA is authorized to overrule a COE permit decision under the current language of the CWA (Section 404(c) and 40 CFR 231).

In addition to permit and enforcement activities, the COE participates in limited investigative, research, and monitoring activities. Most of the investigation and research activity is directly related to the COE dredging program and management of the Section 404 permit program (e.g., wetland determination, protection, mitigation, or enhancement techniques). Water quality monitoring has traditionally addressed conventional pollution parameters such as turbidity, dissolved oxygen levels, etc. Priority pollutants and other pollutants are generally not

addressed unless a case study specifically addresses these as part of a sediment chemistry analysis.

National Oceanic and Atmospheric Administration

Several separate entities within the National Oceanic and Atmospheric Administration (NOAA) address water quality concerns in Puget Sound. A major research program, Marine Ecosystem Analysis (MESA), was managed by the Office of Marine Pollution Assessment (OMPA) and supported numerous, extensive water quality-related studies in Puget Sound. OMPA has recently been dissolved and its functions absorbed by the Ocean Assessment Division, an entity within the National Oceanic Service (NOS). The MESA program has contributed much in the way of scientific expertise on marine pollution and as a funding source for pollution investigations and research in Puget Sound. Another NOS group, the Pacific Marine Center, is responsible for research and updating charts and tidal information within Puget Sound.

The Northwest Region of the National Marine Fisheries Service (NMFS) has two roles in water quality management of Puget Sound. The Northwest and Alaska Fisheries Center, through its Environmental Conservation Division, conducts research and investigations which include the affects of pollutants on fisheries. NMFS is also the regulatory arm of NOAA, and comments on permit applications by authority of the Fish and Wildlife Coordination Act (16 USC 661 et seq.), the Marine Mammal Protection Act (16 USC 1361 et seq.), and the Endangered Species Act (16 USC 1531 et seq.).

NOAA's Office of Research and Development has also performed several research projects within Puget Sound through the Pacific Marine Environmental Laboratory. These efforts are apart from NMFS- and MESA-sponsored studies.

U. S. Fish and Wildlife Service

The U. S. Fish and Wildlife Service (USFWS) has an advisory role in water quality management of Puget Sound by commenting on permits under authority of the Fish and Wildlife Coordination Act. The National Fisheries Research Center (NFRC) laboratories carry out investigations and research on contaminant-related issues in support of various USFWS activities; however, the studies typically relate to freshwater systems and are often issue-oriented rather than site-specific work. In terms of direct relevance to Puget Sound, the NFRC laboratory in Columbia, Missouri, has been involved in research analyzing impacts of arsenic on anadromous fish. The local NFRC laboratories and the USFWS also provide advice and information relative to the design, conduct, and preparation of

environmental impact assessments as these relate to water quality impacts on fish and wildlife.

U. S. Coast Guard

The U. S. Coast Guard (USCG) 13th District participates in water quality management of Puget Sound by issuing permits for structures under Section 9 of the Rivers and Harbors Act, reviewing COE Section 404 permits in navigable waters under Section 10 of the Rivers and Harbors Act, and deploying an oil spill response team as needed.

The major role of the USCG in pollution control is monitoring for and emergency clean-up response to oil spills, and enforcing wastewater disposal by vessels. The USCG relies on WDOE to certify that a proposed project will not violate state water quality criteria before issuing a permit under Section 9 of the Rivers and Harbors Act. The USCG can comment on the COE dredge and fill (Section 404) permit, but usually does so only from the standpoint of marine safety and navigation. Pollution prevention also plays a minor role in USCG review and approval of operating manuals (procedures) for marine transfer (port) facilities. This review and approval is usually post-construction, and is required before a facility can begin operation. The USCG is also involved in enforcing regulations on marine sanitation devices and the discharge of bilge water by vessels.

Food and Drug Administration

The Food and Drug Administration (FDA) indirectly contributes to water quality management in Puget Sound as a result of FDA's responsibility for regulating impurities or contaminants in seafoods. The role of FDA differs between certain shellfish (fresh or frozen oysters, clams, and mussels) and other seafood. For certain shellfish, FDA acts on an advisory basis, providing guidance or technical expertise to state, local, or industry groups seeking to establish standards for shellfish growing or harvesting waters. For these shellfish, the FDA program is voluntary and depends on state or county monitoring and enforcement. FDA may conduct laboratory analyses or provide work space for water quality monitoring as it pertains to shellfish growing beds, and publishes a list of certified shellfish shippers. For other seafoods, FDA established on a regulatory basis permissible levels of residues on a product-by-product and contaminant-by-contaminant basis. These residue levels are enforced by FDA under authority of the Federal Food, Drug, and Cosmetic Act (21 USC 342[a]). A few organic compounds or heavy metals are covered by administrative guidelines, rather than by enforceable regulations.

Although FDA may be asked to comment on permit applications for activities proposed near shellfish beds, there is no established mechanism for soliciting this input. FDA has established a research facility in the Seattle area to assess the quality of seafood reaching the marketplace. The objective of this program is to develop a methodology for detecting contaminants in problem areas and determining whether detected amounts exceed expected background levels in seafood. Budget and staffing constraints have currently limited this investigative and research effort.

State Agencies

Department of Ecology

Congress clearly stated in the FWPCA, and subsequently the CWA of 1977, that the responsibility for managing the publicly-owned sewage treatment works construction grant program and implementing certain permit programs would be delegated to the states following EPA approval of the state's program. In 1973, EPA delegated much of the responsibility for the NPDES permit program (Section 402) to the State of Washington. The NPDES system is operated by WDOE and replaced the state's prior discharge permit program. In 1979, WDOE assumed responsibility for the Construction Grants Management Assistance Program. WDOE also is responsible for establishing water quality standards (Section 303) which effectively classify waters of the state into one of several categories reflecting beneficial water uses.

The mission of WDOE includes water, air, and land resource management and stewardship. This responsibility is authorized by the State Environmental Policy Act (SEPA) and implementing guidelines (WAC 197-10). Overriding priorities in fulfilling WDOE's mission are: 1) to protect public health, 2) to preserve environmental quality, and 3) to ensure full and proper utilization of natural resources for the benefit of all citizens. The current approach to addressing these priorities in reference to water quality is to focus on: permitting; compliance assurance and enforcement; wastewater facilities plan review; and water pollution control grants activities, especially as these activities relate to the control of toxic pollutants. It is clear that the stated mission of WDOE results in broad responsibilities for aquatic resources in Puget Sound, responsibilities which may overlap to some extent with other agencies. In effect, WDOE plays a three-part role in water quality management: 1) it implements federally-mandated programs that may be carried out by the state and also influences federal activities by determining whether federal activities meet state water quality standards; 2) it addresses water quality issues as mandated by state law, and 3) it acts as the state clearinghouse for state and local agency input related to water quality issues.

WDOE is responsible for a number of programs that address water quality concerns relevant to Puget Sound. Many of these directly relate to Puget Sound or relate to point source discharges; others may seek to control nonpoint sources of pollution or indirectly affect Puget Sound. A partial list of programs or activities is found in Table 2-1.

As part of the NPDES permit application, each discharger is required to fill out a form which characterizes the discharge for EPA. Point values are assigned by EPA according to various attributes of the discharge as described by the form. If the total number of points exceeds 80, the discharger is classified by EPA as a major discharger, rather than a minor discharger. The definition of major and minor has varied in the past. WDOE does not use the point system for identifying major discharges, rather WDOE and EPA annually determine which dischargers will be subject to Class II major discharger or Class I minor discharger inspections. Classification depends on budget and manpower constraints, historical record, and type of discharge. Class I dischargers are subject to visual inspection of operation and maintenance (O&M) of the facilities by WDOE. During the Class II inspection, WDOE inspects the facilities, reviews operations and analytical procedures, tests effluent and receiving water, and verifies compliance with permit conditions. If discrepancies are noted, enforcement action is taken if sufficient data are available. If more data are needed, a Class III inspection (i.e., a reinspection) is initiated. If discrepancies are again noted, WDOE initiates a Class IV inspection, which gathers data for enforcement activity.

Department of Fisheries

The Department of Fisheries (WDF) is responsible for managing various fishery resources in Puget Sound and, therefore, is concerned with water quality issues as they relate to fishery resources. The fisheries managed by WDF include shellfish, most truly marine finfish, salmon, sturgeon, and food fish ("nongame") species in marine and freshwater. Although WDF may conduct extensive water quality investigations and research related to these fisheries, WDF relies heavily on WDOE and EPA for implementing water quality decisions, and participates in water quality decision making by engaging in permit review. Jurisdiction is limited to marine areas below mean higher high water (MHHW) and freshwater areas below ordinary highwater. WDF can recommend approval, disapproval, or request modifications of proposed project plans through the permit review process.

Although WDF has no jurisdictional authority over activities above MHHW, the agency may be involved in shoreline planning if WDOE seeks input from WDF, especially on matters related to sedimentation, storm drain discharge, and the use of septic tank systems.

Table 2-1. WDOE Water Quality-Related Programs/Activities

	Established	Under development	Under revision	Point source (Direct)	Nonpoint source (Indirect)
NPDES permit program	X			X	
Section 201 construction grant program	X			X	
Water quality standards, certifications, variances (permit review)	X			X	X
Puget Sound water quality management program*	*	*	*	X	X
Oil and hazardous materials spill response capability	X			X	
Toxics monitoring program			X	X	X
Toxicant pretreatment program		X			
Shellfish protection program		X		X	X
Coastal zone management program	X			X	X
Air quality management program	X				X

*There are a number of water quality management plans funded by CWA grants. Their status varies.

Department of Game

The Department of Game (WDG) is responsible for managing certain sportfish species, including steelhead trout. The role of WDG in water quality decision making is very similar to that of WDF; permit review is usually a joint undertaking by WDF and WDG. In the case of Puget Sound resources, WDG is most clearly involved in water quality decisions pertinent to steelhead trout.

Department of Social and Health Services

The Department of Social and Health Services (DSHS) plays a role in water quality management to the extent that the agency is responsible for protecting public health. The office of Environmental Health Programs in DSHS is responsible for certifying that water quality criteria are met in all commercial shellfish growing areas. DSHS participates in some water quality investigation and research work, but relies primarily on commercial operators to do water quality monitoring for commercial shellfish beds. The major emphasis is placed on fecal coliforms as an indicator of probable occurrence of health-endangering viruses, and on paralytic shellfish poisoning (PSP) caused by red tides. The DSHS may also conduct shoreline investigative surveys near growing areas to identify sources of pollution potentially threatening certification of growing areas, but relies on local (county) enforcement if local jurisdiction is appropriate (e.g., failed septic tanks, illegal land use activity).

The DSHS may comment on NPDES permits and Section 301(h) waivers, but rarely does so. No formal notification process occurs between WDOE and DSHS. Notification is made through the normal public notice, unless DSHS District Engineers request that copies of NPDES permits be regularly forwarded. WDOE has noted that DSHS involvement has been limited to domestic or municipal discharges near shellfish beds (Springer pers. comm.); most input to WDOE from DSHS has been given in response to facilities plans near shellfish beds. DSHS apparently has not been involved with industrial discharge permit review.

Department of Natural Resources

As manager of submerged lands and tidelands, the Department of Natural Resources (DNR) negotiates and issues leases for mariculture operations, prepares harvest agreements for commercial shellfish beds, and manages open water dredge disposal sites. Preparation of harvest agreements is carried out in conjunction with WDF and DSHS; the latter certifies that the area is safe relative to water quality criteria. Dredge disposal sites are approved by a multi-agency review process and

managed by DNR. Section 404 permits for dredge disposal must be obtained from the COE (Hansen, pers. comm.). DNR generally does not participate in water quality research, but is involved as it pertains to its pilot research program on seaweed culture. Major effort is now focused on the culture of Porphyra (nori).

Local Agencies

County Departments of Health

County health departments are responsible for certain local water quality programs affecting Puget Sound. These departments are heavily involved in PSP monitoring programs in shellfish beds harvested by sport fishermen. They also may monitor activities and enforce local ordinances which address public health concerns (e.g., septic tank systems).

Local Planning Commissions

Local planning commissions are responsible for local land use ordinances and, therefore, play an important role in permitting or regulating point and nonpoint sources of pollution. The extent and significance of their role varies widely between the numerous jurisdictions surrounding the Puget Sound study area. The Municipality of Metropolitan Seattle (Metro) and SNOMET/King County have been designated by WDOE as local agencies responsible for water quality planning and management within their respective jurisdictions.

Municipal, Domestic, and Industrial Dischargers

In addition to compliance with treatment requirements, dischargers are responsible for providing certain required data as part of the NPDES permit application and to monitoring the discharge (effluent and receiving water) according to conditions attached to the issued permit. Under existing federal and state regulations, dischargers seeking renewal of an NPDES permit or a 301(h) waiver also must provide data on the levels of priority pollutants in the effluent.

Monitoring requirements vary according to the type, size, and significance of the discharge, and are decided on an individual basis. Some dischargers have numerous limitations imposed on the discharge but are required to do little monitoring; other dischargers may have few limitations imposed, but are required to carry out extensive monitoring.

In addition to carrying out prescribed monitoring programs, municipal dischargers may serve a local regulatory role by restricting certain practices through municipal sewer use ordi-

nances. These ordinances restrict or prohibit discharges of certain materials into the wastewater stream which may interfere with the collection and treatment system or endanger public health. Enforcement is usually obtained through a system of fines or penalties.

Tribal Agencies

Recent federal court cases have radically changed the role of Indian tribes in state and federal management of fisheries in Puget Sound. The recent Orrick decision (United States v. Washington 1980) affirms Indian rights to protect salmon and steelhead runs from adverse environmental impacts. Although this ruling has been appealed, it has great potential to radically alter the role of tribal government in making water quality management decisions for Puget Sound.

Summary

The responsibility for water quality management of Puget Sound is vested in a number of federal, state, and local agencies (Table 2-2). Although no one agency clearly orchestrates the efforts of all toward a common goal, WDOE plays a major role through administration of state water quality guidelines. It would appear that the only unifying efforts among the agencies are: 1) the common objective of preserving or maintaining a healthy environment, and 2) permit review via the public notice process.

WDOE and the COE perform major clearinghouse roles at the state and federal permit review level. The permit review process is generally limited by the tendency for each agency to focus attention on specific resource management actions. For example, DSHS is interested in water quality impacts on commercial shellfish beds. Commercial beds do not occur throughout the Sound, and only those DSHS districts with commercial beds may express interest in reviewing NPDES permits or 301(h) waiver applications. No formal notification of permit review exists between WDOE and DSHS unless the DSHS District Engineer requests that automatic notification occur. In most cases, notification is limited to municipal and domestic dischargers, since major concerns for shellfish have historically been fecal coliform levels and PSP, and not other pollutants. Although not fully understood, but nevertheless of potential major consequence, is the recently affirmed right of tribal governments to influence water quality decisions as they affect salmon and steelhead fisheries.

The environmental legislation having the most widespread impact and greatest relevance to Puget Sound is the Clean Water Act (CWA). The Act and its implementing regulations mandate water quality, effluent limitation, and industrial performance

Table 2-2. Overview of Typical Agency Roles in Water Quality Management of Puget Sound

Level of Government	Agency	Regulation Promulgation	Enforcement	Permit Issuance	Permit Review	Investigation	Research	Monitoring
F	EPA	M	M	D	M	M	M	D
F	COE	M	M	M	M	Limited to Section 10 & Section 404	Limited to Section 10 & Section 404	Limited to Section 10 & Section 404
F	NOAA	A	Limited to marine mammals	None	A	M	M	A
F	USFWS	A	None	None	A	Limited to anadromous fish	Limited to anadromous fish	A
F	USCG	Limited to Section 9	M	Limited to Section 9	A	Limited to oil spills and vessel discharge	None	Limited to oil spills
F	FDA	Limited to seafood	Limited to seafood	None	None	Limited to seafood	None	Limited to seafood
S	WDOE	M	M	M	M	M	None	M
S	WDF	None	Limited to fisheries	A	A	Limited to fisheries	Limited to fisheries	None
S	WDG	None	Limited to fisheries	A	A	Limited to fisheries	Limited to fisheries	None
S	DSHS	Limited to commercial shellfish operations	Limited to decertification of shellfish beds	Limited to certification of shellfish beds	A	Limited to commercial shellfish	Limited to commercial shellfish	None
S	DNR	None	None	None	None	None	Limited to noriculture	None
L	County health departments	None	Limited to local ordinances	None	A	Limited to public health	None	Limited to public health
L	Planning commissions	Land use ordinances; designated local 208 agencies	None	Limited to land use ordinances	A	None	None	None
L	Dischargers	Limited to sewer use ordinances*	Limited to sewer use ordinances*	None	None	Limited to permit applications	Optional	As required by permit
L	Tribal agencies	P	P	P	P	Limited to fisheries	Limited to fisheries	P

M - major role
A - advisory role
D - delegated role
P - potentially major
F - federal
S - state
L - local or tribal

*Except for Section 208 planning by Municipality of Metropolitan Seattle.

standards; provide grants for point and nonpoint source permit and control programs, and for construction of publicly-owned waste treatment works; and authorize a number of other water quality management activities. EPA retains responsibility for all CWA activities, but delegates implementation to many other federal and state agencies including the U.S. Army Corps of Engineers (dredge and fill permit program); the Washington Department of Ecology (construction grants, water quality standards, nonpoint source planning, NPDES permits); and the U.S. Coast Guard (marine sanitation devices).

Water quality investigation, research, and monitoring efforts are fragmented and generally limited to specific resource management actions of importance to the sponsoring agency. In these three efforts, more than in other management activities, there is little coordination between various agencies. The National Oceanic and Atmospheric Administration has played a major role in water quality investigation and research in Puget Sound through the Marine Ecosystem Analysis (MESA) program. This program was funded by Congress as a line-item appropriation, and has contributed much in the way of research and investigative activity beyond the typically narrow scope of specific resource management objectives.

Chapter 3

OVERVIEW OF DATA BASE REQUIREMENTS

The objective of EPA and WDOE is to make water quality management decisions based on a systematic evaluation of the predicted environmental impacts of their regulatory activities. These activities include: issuance or renewal of NPDES permits for municipal and industrial discharges; Superfund program decisions; evaluation of Section 301(h) waiver applications; permit compliance and enforcement activities; control of nonpoint sources of pollutants; permit review; and other environmental activities. Implicit in this objective is the desire to make decisions with full knowledge of the cumulative impacts of regulatory decisions with reference to the assimilative capacity of Puget Sound for pollutants.

Definitions

Before pursuing a description of the data needed to achieve this objective, it is imperative that certain terms be clearly defined. Some key terms used in this report are defined below:

Pollutant. The definition used here is generally that found in Section 502 of the CWA. Pollutants include a broad range of materials, chemicals, and heat which alter the naturally occurring physical, chemical, or biological characteristics of the water body.

Toxicant. This term is frequently used but rarely defined rigorously. A toxic substance is one that impairs, injures, or kills an organism by interfering with a body or cellular function. This definition, however, becomes almost useless if one considers that almost any substance can be toxic in excessive amounts. In most toxicological literature, the term "toxicant" is generally used to refer to chemical compounds that harm or kill at relatively low concentrations when taken up or ingested by an organism.

Contaminant. This term is used here to refer to pollutants in potential foodstuff or in the environment that endanger public health at relatively low concentrations or otherwise render the environment unfit for certain beneficial uses. These are substances which have been found to induce infectious illness or disease (e.g., bacteria, viruses), cancer (carcinogens), chromosomal damage (mutagens), or congenital deformities

(teratogens) in laboratory studies with test organisms or in epidemiological studies on humans.

Direct Effect. Although the term is self-explanatory, it is often overlooked that direct effects occur as pollutants act on individual organisms or certain beneficial uses. A direct effect on organisms usually results from a biostimulatory or toxic action of the pollutant. Direct effects on beneficial uses may include a wide array of impacts, particularly on aesthetics (e.g., turbidity may directly affect the use of water for aesthetic enjoyment) and water-contact recreation. Habitat also may experience direct effects when habitat is defined by standards or environmental requirements of particular species as a beneficial use. However, habitat may also be the pathway of indirect effects on individual organisms.

Indirect Effect. A pollutant may not affect a beneficial use or species toxicologically, but may exert an adverse impact on that species by eliminating an important food species that is sensitive to the pollutant. These changes may be seen as indirect effects and, as noted later, they are typically difficult to document (Suter 1981), especially in the marine environment. Indirect effects on individual organisms can be perceived as changes in the community structure or productivity. Indirect effects on beneficial uses are generally observed as losses at the population or habitat levels which are of clear concern to human uses.

Cumulative Impact. This term refers to the environmental impact resulting from the sum of the activities occurring in or tributary to the impacted area. It also refers to the total effects observed at all levels within the impacted environment, i.e., the sum of the direct and indirect effects as defined above. Making management decisions based on predicted cumulative impacts implies that decision makers understand how the environment will respond to the cumulative effects of their decisions. Management decisions usually imply that permitted disturbances to the environment will be assimilated before measurable changes occur.

Assimilative Capacity. This term has been used in two different ways. In one usage, the term refers to the maximum amount of pollutant the system can process without disrupting normal ecological relationships. This usage is theoretically satisfying from a scientific perspective, but it poses difficulties for resource managers because many ecological relationships are too subtle to be detected or are simply poorly understood. A second usage, evolved in partial response to this difficulty, defines assimilative capacity as the maximum amount of pollutant the system can process without producing an unacceptable biological impact. Unacceptable biological impact generally refers to impairment of a specific beneficial use. This usage is much more satisfactory from the perspective of the resource manager because it allows for a clear definition of

unacceptable impact. It is important to note, however, that this definition refers primarily to a system of socially defined values, i.e., beneficial values. The role of science is often limited to tracing the steps between release of pollutants and their ultimate effects on beneficial uses of value to society, and to assisting in making the best available judgement.

Conceptual Framework

One of the requirements for successful resource management is to develop a cost-effective method to monitor and evaluate the status of the resource, i.e., a method that yields the greatest amount of useful information per unit cost. A second requirement is to obtain data to demonstrate that a particular anthropogenic activity is significantly advantageous or detrimental to a beneficial use of the resource. In the case of living resources, both requirements usually have in common the need to examine the ability of certain organisms to survive, grow, and reproduce, i.e., display biological continuity.

Quantitative knowledge of natural phenomena is essential to any credible analysis of pollution effects. In marine ecosystems such as Puget Sound, impact assessment and monitoring at the population or community level of organization (the holistic approach) are challenging: because change through natural variation is the normal state, and because it is difficult in many cases to distinguish between natural and anthropogenic change and variation. Subtle, natural changes in oceanographic conditions, for example, may markedly alter community composition in plankton, including the distribution, survival, and settlement of larvae. Large quantities of money and manpower have been spent fruitlessly while trying to quantify changes in biological communities as a result of man's activities because natural variation was not also described. If anthropogenic change is to be identified over the background of natural variation, data are needed to link the change to a causal agent. The alternative reductionist approach that attempts to document effects by examining biochemical changes in cells or body fluids often fails for similar reasons, because of difficulties in linking biochemical change to meaningful alterations in survival, growth, or reproduction of the organism. Although these and other complex approaches are worthwhile endeavors in water quality management, their results are often of more interest to scientists than to decision makers. These kinds of data are essential, however, to the improvement of theory and the construction and calibration of holistic models of the ecosystem. The resolution of immediate problems typically results in the investigation of tangible, direct effects. The concept of direct effect, as defined by changes in beneficial uses or the ability of organisms to maintain biological continuity, plays a major role because these effects are most amenable to scientific investigation. They also provide opportunities to test theories and models.

Analyses of direct effects on individual organisms or beneficial uses, however, do not and will not serve as the sole source of information or the cure-all approach to water quality management. Analyses of direct effects do serve as the crucial first step. To manage water quality of Puget Sound, data are needed that sequentially: 1) disclose an effect on beneficial uses or biological continuity of organisms; 2) permit resource managers to trace the causal agent to its source; and 3) suggest remedial actions. Data on direct effects are then used in holistic models to improve the capacity of the decision making relative to predicting indirect effects and cumulative impacts.

Data Required for Cumulative Impact Evaluation

The basic need for predicting cumulative impacts, assessing environmental effects, and monitoring for changes attributed to pollutants is a quantitative understanding of linkages between: mass loading; the physical, chemical, and biological fate of a specific pollutant; its direct effects on individual organisms and habitats; and, ultimately, effects on beneficial uses. A conceptual diagram of these linkages is found in Figure 3-1. In this conceptual diagram, the scientific approach can be used to describe and quantify:

- Sources of pollutants
- Natural or uncontrollable mass loading
- Controllable mass loading
- Transport processes (diffusion, circulation, advection)
- Physical-chemical fate (adsorption, speciation, redox reactions, photolysis, etc.)
- Distribution in the physical environment
- Biological uptake (bioavailability, bioaccumulation, biomagnification)
- Metabolic processes (biodetoxification, biodegradation)
- Distribution in the biota (bioaccumulation)
- Dose-response data (growth, behavior, death)
- Synergistic effects (between toxicants and as a function of organism stress)
- Effects on individual organisms (mortality, sublethal toxicity)

A key feature of the necessary data base as diagrammed in Figure 3-1 is that both scientists and resource managers must consider human interests as a key link in resource management. If a linkage between a potential pollutant and adverse effects on a beneficial use cannot be demonstrated, then resource management becomes more arbitrary and less scientific. Resource impact assessment should have as its end-point data that can be used to judge whether the predicted impact on a resource is acceptable or unacceptable.

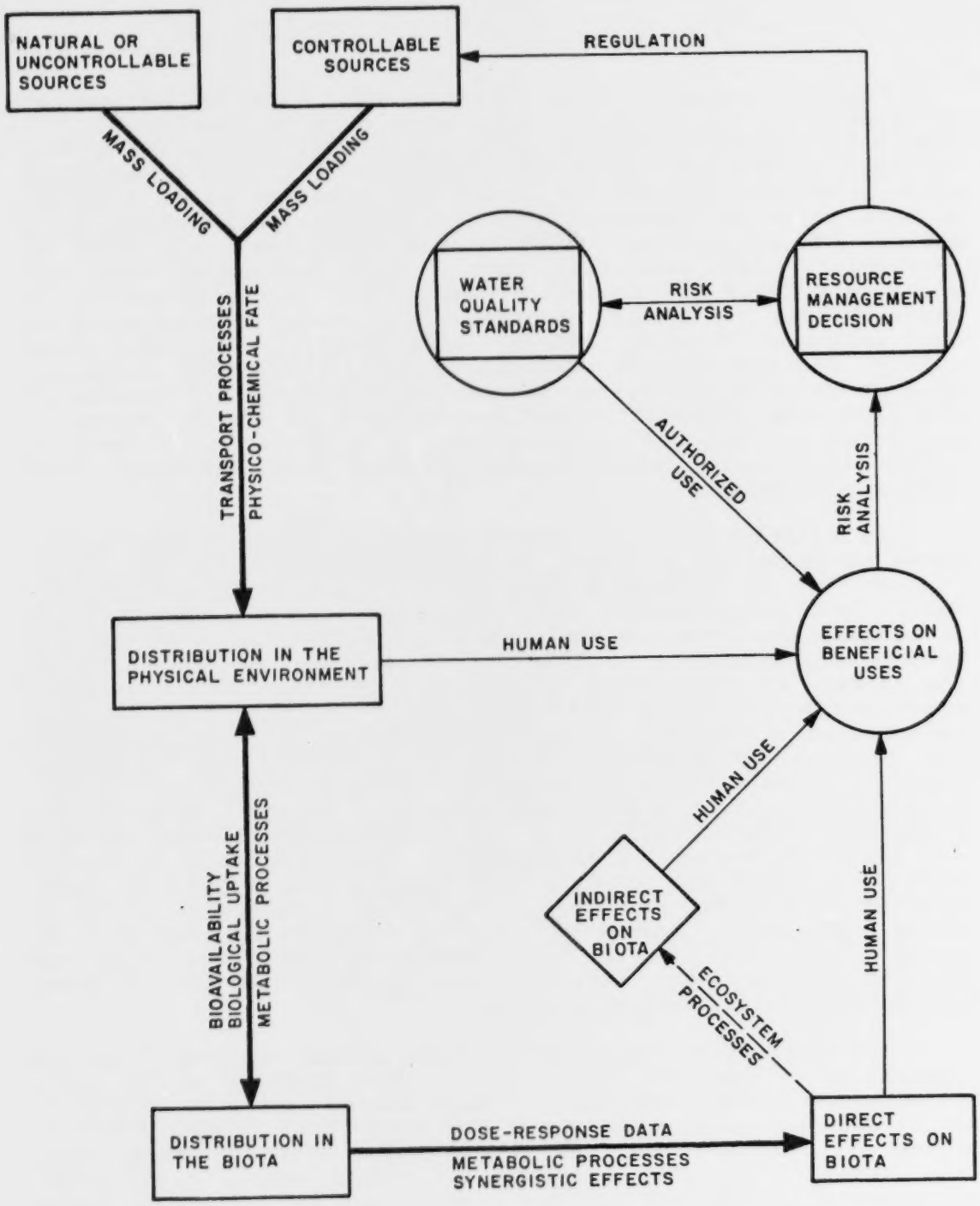


Figure 3-1. Diagram of Linkages Between Data Needed for Water Quality Management Decisions

NOTE: Boxes and bold arrows represent descriptive compartments and processes which can be quantified. Ecosystem processes (broken arrow) and indirect effects (diamond) are open to scientific analysis but rarely quantifiable. The circles and remaining arrows represent compartments or processes that are defined or implemented within the social framework (modified from White and Lockwood, in press).

Provided suitable data are available, resource management decisions can be based on some type of risk analysis. The degree of sophistication in risk analysis is a function of the efficacy of the scientific information used in its formulation as well as the purpose for doing the risk analysis. Although science plays an important role in risk analysis and decision making, it can be constrained by the social setting. This is particularly the case when two or more beneficial uses are weighted differently in social importance. Decision making in water quality management is often based on an understanding of how pollutant loading affects human health, economy, food supply, recreation, and aesthetic sensitivities. The preservation of the pristine system may be the most desirable beneficial use from some viewpoints, but may be moot if the discharge of pollutants is allowed or permitted as a result of a need to reduce impacts on other beneficial uses (e.g., economy, food supply, recreation).

In addition to the need to consider socioeconomic influences on technical problems, a second key feature in the establishment of an effective data base is the obvious need for multi- and inter-disciplinary approaches in the research and investigations that supply data. Certain common goals and methods are needed to provide meaningful data necessary to link the loading of a particular pollutant with effects on individual organisms and/or beneficial uses. Figure 3-1 can be misleading because, as a schematic, it oversimplifies the quantity of data and breadth of expertise needed to document such linkages. There is a need for an inter-disciplinary framework to coordinate studies into a quantitative, holistic system. Without this framework, data emerging from individual, uncoordinated efforts are often inconsistent, incompatible, and difficult to use in documenting linkages between mass loading and effects on organisms or beneficial uses. If a coordinating framework is not in place, individual investigators are expected to continue to confine their efforts to their fields of expertise; thus, the resulting information will continue to be fragmented in time, place, conditions, and methodology.

The predictive value of working models derived from the general model outlined in Figure 3-1 is a function of the sizes of sampling errors for various data sources and the extent to which assumptions are made to reduce work loads or data requirements. In certain features, e.g., point source loading data, the data can be very precise. In other areas, e.g., dose-response data, the conclusions always must be couched in terms of statistical probability. The reliability of the predictive output of models can never be more precise than the sampling error or degree of uncertainty at the weakest point in the model. Table 3-1 summarizes the general types of data needed to implement a holistic modelling effort.

Table 3-1. Data Needed to Implement Water Quality Management Actions Relevant to Cumulative Environmental Impacts of Regulatory Decisions

Compartment or Process	Data Needs	Approach: Investigation	Approach: Research	Approach: Monitoring	Remarks
Sources of pollutants	Inventory of all source categories	X			Basis for current and future analyses.
Uncontrollable mass loading	Functional definition of uncontrollable; may vary with specific modeling effort.				Value judgement.
	Annual input rate, seasonal rates if temporal.	X		X	Comprehensive characterization of loads, if loading rates needed for current and future analyses.
Controllable mass loading	Input rates by month; assignment of priority to pollutants known to be of direct concern to beneficial uses.	X		X	Comprehensive characterization of loading needed for current and future analyses; priority determined by detection of effects on beneficial uses (e.g., seafood or recreational areas) and value judgement.
Transport processes	Data for design and operation of models predicting diffusion, advection, circulation, and sediment deposition rates.	X	X	X	Models must cover nearfield and farfield tributary area (water mass) in detail. Broadly scoped models of the Sound can be less refined. Sensitivity analysis and verification must be demonstrated before use in regulatory decisions.
Physico-chemical fate	Estimate rates of adsorption/desorption, hydrolysis, speciation, precipitation/dissolution, volatilization, photolysis, redox reactions.	X	X		Results need to be couched in terms of confidence level probabilities.
Distribution in the physical environment	Linkages between loading and distribution must be demonstrated.	X		X	
Bioavailability	Identify physical/chemical processes that make pollutants either available or unavailable, and estimated rates.		X		Knowledge of processes can be qualitative.
Biological uptake	Rates of bioaccumulation and biomagnification; basic knowledge of food chains and experimental examination of uptake mechanisms.	X	X	X	Knowledge of food chains and uptake mechanisms (ingestion, absorption) can be qualitative. Rates of bioaccumulation and biomagnification must be quantitative.
Metabolic processes	Methods and rates of depuration, biodetoxification and biodegradation; metabolic byproducts.	X	X	X	A factor in prediction of effects and estimation of assimilative capacity.

Table 3-1. (Continued)

Compartment or Process	Data Needs	Approach: Investigation	Approach: Research	Approach: Monitoring	Remarks
Distribution in the biota	Linkage between distribution in the physical environment and distribution in biota; distribution by geographic area and by tissue type or body organ.	X		X	Priority on species known to be of direct concern to beneficial uses, especially to human consumption and economics (fisheries).
Dose/response data	Use of appropriate species; documented relationships between laboratory and field studies; use of standardized techniques; investigation of effects on mortality, growth, reproduction, and migration.	X	X	X	Deemphasis on pollution-tolerant species or inappropriate sentinel species. Data must be in terms of confidence level probabilities. Laboratory conditions must be appropriate to field conditions.
Synergistic effects	Between toxicants; under range of probable environmental conditions (stress).		X		Development of multidimensional response surfaces (using combined dose/response curves). Data must be in terms of confidence level probabilities.
Effects on biota	Linkage between distribution in biota and observed mortality or sublethal toxicity.	X	X		

Examples of Problem-Solving Approach

A key feature of the comprehensive model approach described above is that the focus of the scientific effort is toward quantitatively documenting linkages between pollutant loading and effects on individual organisms or beneficial uses. The objective of this approach is to develop a scientific statement about environmental effects that is expressed in appropriate probability terms, where model elements are tied together by logical design, and where results can be judged for use by resource users and managers. The linkage can be pursued in one of two ways: one approach is to identify a particular discharge or pollutant and determine its effects; the other approach is to identify an effect (change in beneficial uses or biological continuity of organisms) and then attempt to determine the cause. The latter approach is most likely to be more cost effective.

The implication of this latter approach is that priority problems enter the model initially as known effects on a beneficial use, (e.g., reduction of a fishery), or on organisms. The approach then to problem solving is to identify the causal agents and trace them backward to their sources. In some cases, the direct effect on individual organisms or on a beneficial use is readily identified, and the causal agent can be traced with clearly defined effort. For example, a fishery may be adversely impacted because the FDA has determined that levels of a specific contaminant in seafood approach or exceed those considered safe for human consumption. To remedy this situation, the source must be found and abated. The priority effort is to discover where and how the contaminant is taken up; the route taken by the contaminant from source to the point of biological uptake; and the time necessary for the seafood to become edible again. In some cases, the direct effect is on beneficial uses and not on the biota. For example, certain areas may be unsuitable for water-contact recreation because of high concentration of fecal coliforms, which suggests that human pathogens may be in the water.

The multi-disciplinary approach is particularly fruitful if beneficial uses are impacted through indirect effects; for example, the loss of a fishery because of changes in quality or quantity of prey or changes in competitive ability between species. In such cases, long-term multi-disciplinary research may be necessary. Initial effort may focus on determining whether correlations between observed pollutant conditions and effects may be identified. If the multi-disciplinary effort can show that the correlation is biologically meaningful and not spurious, it may be possible to initiate interim remedial action on pollution sources based on the observed correlation.

Summary

Water quality management is normally accomplished by a statutory permit/enforcement program. Ideally, water quality management decisions should be made with full knowledge of the direct and cumulative impacts expected to result from each decision. Knowledgeable decisions require data of several kinds: location and type of pollutant sources; quantity of each potential pollutant discharged; physical, chemical, and biological processes affecting pollutant transport and environmental fate; pollutant distribution and concentrations; toxicity/dose-response data for key species likely to be affected; and synergistic effects of pollutants. This information will allow a reasonable determination of the maximum loading a system can absorb before an unacceptable biological impact occurs.

Because many ecosystem impacts are difficult to observe or quantify, "unacceptable impact" is most efficiently defined as impairment of a designated beneficial use, or alteration in the ability of certain organisms to survive, grow, and reproduce. These represent key starting points in impact assessment and resource management.

The data base should have two key features: it should contain data which can demonstrate relationships between pollution and effects on beneficial use; and it should be based on a coordinated multi-disciplinary approach so that data are compatible and consistent from study to study.

Chapter 4

MASS LOADING OF POLLUTANTS TO PUGET SOUND

Introduction

Resource managers require information on mass loading from controllable and noncontrollable sources in order to: 1) predict impacts of their decisions; 2) determine whether the impact can be alleviated by control methods; and 3) implement effective control measures. The purpose of this chapter is to summarize the available information on pollutant loadings to Puget Sound. This includes a discussion of the types and number of sources, the nature and extent of currently available mass loading data, and a summary of these data.

Types of Pollutants and Water Quality Indicators

Pollutants and water quality indicators are often grouped into several categories. The following categories will be used in this report:

- Conventional parameters - BOD, pH, oil and grease, total suspended solids, and fecal coliform bacteria
- Extended conventional parameters - COD, nitrogen, phosphorus, temperature, total solids, total nonvolatile solids, and total nonvolatile suspended solids
- Priority pollutants - a list of 126 toxic pollutants developed by EPA (Appendix A)
- Heavy metals and inorganics - naturally-occurring metals and inorganics, some of which are included on the priority pollutant list
- Organic pollutants - primarily synthetic organic compounds, some of which are included on the priority pollutant list. These are often combined into broad categories and include:
  - Pesticides and derivatives
  - PCBs and related compounds
  - Halogenated aliphatics
  - Ethers
  - Monocyclic aromatic hydrocarbons
  - Phthalate esters
  - Polycyclic aromatic hydrocarbons
  - Nitrosamines and miscellaneous compounds

The priority pollutant list and maximum recommended concentrations in aquatic environments were developed as part of a 1976 (modified in 1979) consent decree (Natural Resources

Defense Council et al. v. EPA). At one time 129 toxic compounds were designated as priority pollutants; three compounds were later dropped from the list. The criteria used in the selection of these compounds included: frequency of occurrence in water; chemical stability and structure; amount of the chemical produced; chance for release to the environment; and availability of chemical standards for measurements (Sittig 1980).

Sources of Pollutants to Puget Sound

Pollution can result from anthropogenic (human) activities or natural biological or geological processes. A point source of pollution is defined by regulations as any discernible, confined conveyance, but not including return flow from irrigated fields. Regulatory control is usually exerted through the NPDES permit system. A nonpoint source contributes pollution to the environment in a more diffuse manner, e.g., via groundwater, surface runoff from adjacent land areas, or return flow from irrigated fields. Because of the diffuse nature of the discharge, control is usually exerted through implementation of best management practices. EPA and WDOE further categorize permitted point sources as major and minor dischargers. This distinction is determined by EPA and WDOE during their evaluation of several aspects of the effluent as described in the permit application. The above terms will be used in the following classification of pollution sources to Puget Sound.

NPDES-Permitted Sources

The CWA established the NPDES permit program. NPDES permits with appropriate discharge limitations are issued to point source dischargers. Approximately 240 NPDES permits have been issued to municipal and industrial dischargers in the study area (Figure 4-1). A complete listing of NPDES-permitted discharges in the study area is found in Appendix B. Industrial sources are often subdivided into three categories: noncontact cooling water and storm drainage; process water and wastewater; and combined cooling and wastewater. Review of the data from monitored noncontact cooling water dischargers revealed frequent contamination of noncontact cooling water; therefore, it appeared inappropriate to distinguish between types of industrial dischargers in Figure 4-1 or in the rest of this report because doing so could lead to the misinterpretation that certain industrial discharges (e.g., noncontact cooling water) result in lower mass loading.

Rivers and Streams

Several large rivers and numerous small streams drain neighboring lands and flow into the study area. Rivers and

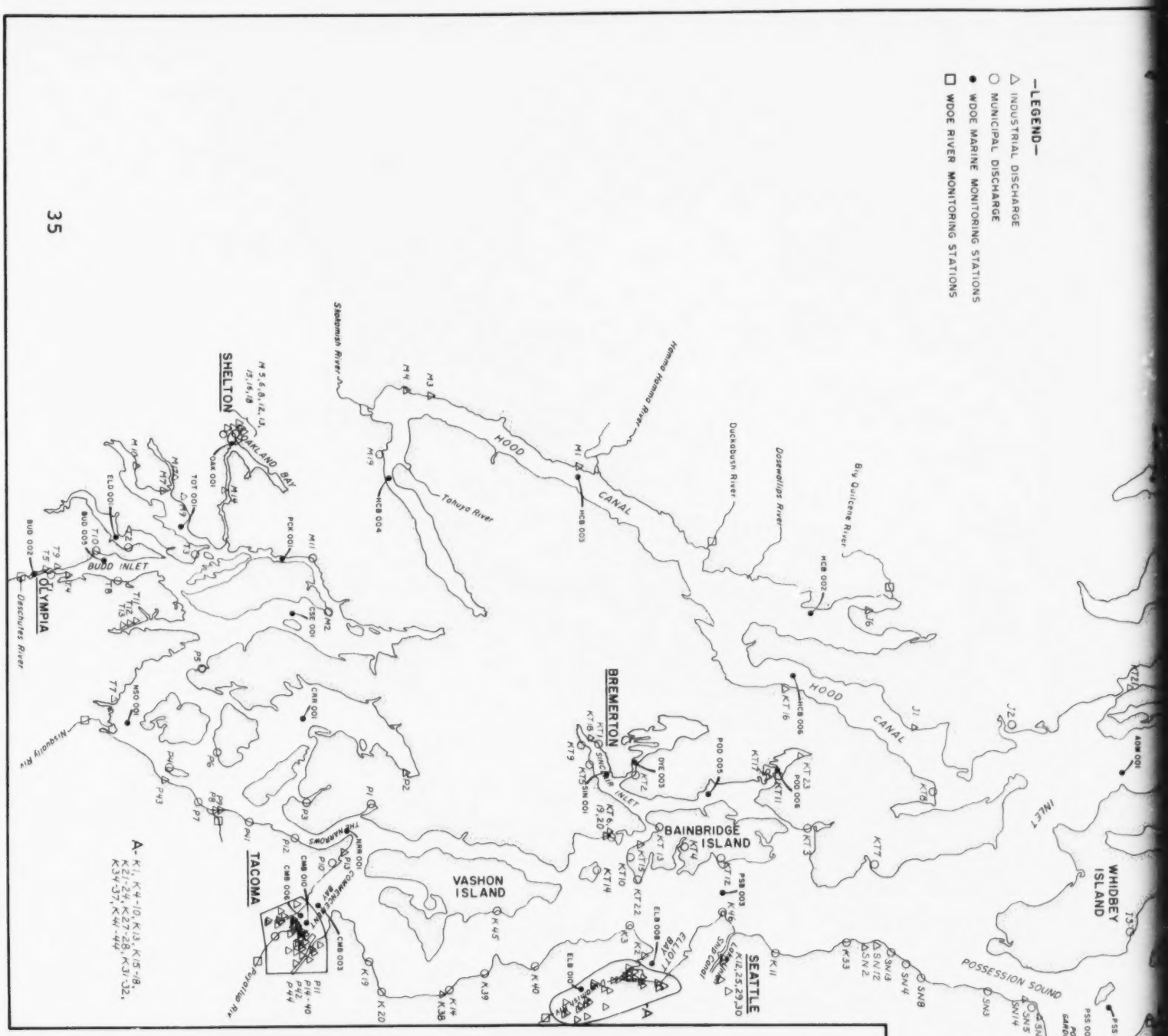
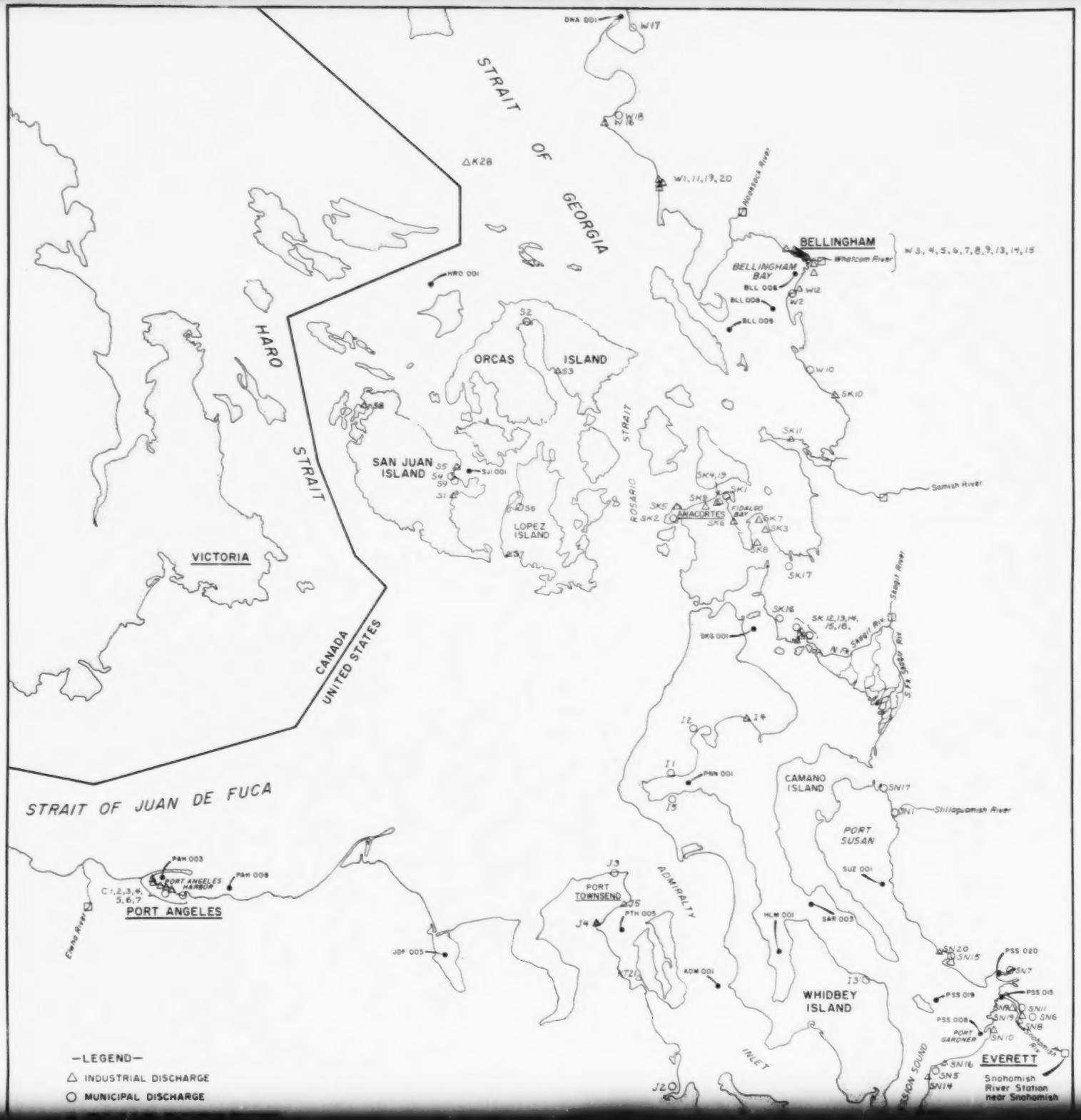


Figure 4-1. NPDES Point Sources and Surface Water Quality Monitoring Stations in the Study Area. Each NPDES Point Source is Identified by County and Number and is Listed in Appendix B


STRAIT OF GEORGIA
HARO STRAIT
STRAIT OF JUAN DE FUCA
CANADA
UNITED STATES
VICTORIA
BELLINGHAM
BELLINGHAM BAY
Whatcom River
W3, 4, 5, 6, 7, 8, 9, 13, 14, 15
ORCAS ISLAND
SAN JUAN ISLAND
LOPEZ ISLAND
ROSARIO STRAIT
ANACORTES
FIDALGO BAY
Samish River
Skagit River
CAMANO ISLAND
PORT SUSAN
Stillaguamish River
PORT ANGELES
PORT ANGELES HARBOR
Elwha River
PORT TOWNSEND
ADMIRALTY INLET
WHIDBEY ISLAND
EVERETT
Snohomish River Station near Snohomish
—LEGEND—
△ INDUSTRIAL DISCHARGE
○ MUNICIPAL DISCHARGE

streams contribute pollutants resulting from anthropogenic and natural sources. For the purposes of this report, these rivers and streams are considered point sources, even though numerous point and nonpoint sources may discharge into the river upstream of the study area. The location of the river discharge as a point source to Puget Sound corresponds to the water monitoring station located nearest the mouth. Figure 4-1 identifies the monitored rivers and appropriate locations of water monitoring stations. Table 4-1 lists the water quality data obtained from these monitoring stations since 1977. A listing of riverine sources to Puget Sound and the study area is found in Appendix C. Common names are included in Appendix C if available; unnamed streams are numbered with the WDF stream number (Williams et al. 1975).

Combined Sewer Overflows

Several municipal wastewater treatment plants with combined stormwater and wastewater systems occasionally experience overflows. These combined sewer overflows (CSO) are often nonpermitted point sources of pollution that do not discharge except when treatment plant capacity is exceeded. Periods of discharge of untreated effluent normally correspond with storm events. Table 4-2 lists the cities in the study area which have combined storm and sewer systems, and therefore are likely to experience CSOs.

Surface Runoff

Precipitation falling on and flowing over surrounding lands conveys potential pollutants into Puget Sound. Urbanized areas collect runoff via stormwater drainage systems and discharge into local streams, the wastewater treatment system, or directly into Puget Sound. Runoff into local streams is included in the mass loading discharge to the Sound from streams and rivers. Runoff entering the wastewater treatment system is covered by the NPDES permit. Storm drains discharging directly into Puget Sound are normally point sources not covered by the NPDES permit system. The exact number of storm drainage discharges has not been determined. Surface drainage, including agricultural runoff, is a nonpoint pollution source discharge to Puget Sound, and it is exceedingly difficult to quantify. Although pollutant contributions of direct surface runoff are probably negligible relative to that carried by storm drain systems, there may be cases (e.g., areas containing hazardous materials dumps, old manufacturing plants, and auto wrecking yards), that have significant adverse effects.

Table 4-1. Discharge and Water Quality Characteristics of Major Tributaries to Puget Sound*

River	Flow Station	Period of Flow Record	cfs Average Annual Flow	Thousand ac/feet/year	Million M^3/year	Temperature range (c°)	DO range mg/l	pH range	Fecal coliform range MPN/100ml	Suspended solids range mg/l	$NO_2+NO_3+NH_3$ range mg/l
Nooksack	Ferndale[a]	1966-1980	3,909	2,832	3,493	2.0-17.5	9.1-13.2	6.4-8.4	56-680[b]	16-280[b]	.08-1.32
Samish	Burlington	1943-1971	243	176	217	0.4-19.8	9.0-13.8	6.7-8.5	19-870[b]	2-100[b]	.64-2.68
Skagit	Mt. Vernon	1940-1980	16,670	12,080	14,901	3.6-19.1	9.7-12.7	6.3-8.4	2-230	6-661	.04-0.38
Stillaguamish[c]	---	---	3,243[c]	2,350	2,899	0-20.3	8.2-14.6	6.1-7.6	---	---	.09-1.39
Snohomish	Monroe[d]	1963-1980	9,855	7,140	8,807	0.1-21.6	8.1-13.2	6.1-8.7	23-3,000[e]	2-130[b]	0-0.73
L. Wash. Ship Canal[f]	---	---	1,343	973	1,200	---	---	---	---	---	---
Duwamish	Tukwilla[g]	1963-1980	1,551	1,124	1,386	6.3-19.8	9.2[h]	7.15[h]	40-1,000	8-150	1.17[h]
Puyallup	Puyallup	1914-1980	3,368	2,440	3,010	2.0-18.6	9.1-13.0	5.9-7.8	0-1,300	3-1,030	.01-0.61
Nisqually	McKenna[i]	1949-1980	1,825	1,322	1,631	3.9-15.3	9.1-12.8	6.8-7.9	7-200[b]	2-18[b]	.06-0.84
Deschutes	Rainier[j]	1950-1975	270	196	241	3.0-22.1	9.3-13.7	6.8-8.3	0-1,000[k]	---	.12-0.93
Skokomish	Potlatch[l]	1977-1980	951	689	850	5.4-12.2	9.1-12.6	6.5-7.7	1-94	---	0-0.21
Elwha	McDonald Bridge[m]	1898-1901 1919-1980	1,506	1,091	1,346	1.2-15.3	9.6-13.4	6.6-8.3	<1-180	1-94	0-0.33

River	Total phosphorus range mg/l	Arsenic kg/day	Cadmium kg/day	Chromium kg/day	Copper kg/day	Lead kg/day	Mercury kg/day	Nickel kg/day	Selenium kg/day	Silver kg/day	Zinc kg/day
Nooksack	.01-.26	---	---	---	---	---	---	---	---	---	---
Samish	0-.17	---	---	---	---	---	---	---	---	---	---
Skagit	0-.25	71	68	245	499	490	4.0	---	0	109	811
Stillaguamish[c]	0-.60	---	---	---	---	---	---	---	---	---	---
Snohomish	0-.08	---	21[b]	41[b]	34[b]	31[b]	7.0[n]	145[b]	---	---	744[b]
L. Wash. Ship Canal[f]	---	---	---	---	5	5	---	3	---	---	14
Duwamish	.22[h]	---	---	6[o]	29[o]	5[o]	---	35[o]	---	---	135[o]
Puyallup	.01-1.5	16[p]	8[p]	58[p]	66[p]	91[p]	0.7[p]	12[b]	0[p]	0[p]	173[p]
Nisqually	.01-.24	4[q]	4[m]	18[m]	9[m]	9[m]	0.05[q]	26	1[q]	0[q]	45[m]
Deschutes	0-.16	---	---	---	---	---	---	---	---	---	---
Skokomish	0-.17	---	---	---	---	---	---	---	---	---	---
Elwha	0-.09	4	4	7	33	44	0.1	2	0	4	92

*All metal loading values based on dissolved plus suspended loads, except for the Nisqually River, which are based on dissolved load only. All samples were not digested; therefore, results are conservative.

Table 4-1. Cont'd.

NOTES: Mass loading of heavy metals is average kg/d. Unless otherwise footnoted, flow and water quality measurements were taken at the same spot, and water quality data are for the period 10/76-9/81.

a = Water quality data taken at Brennan, approximately 4.0 km downstream of Ferndale.

b = 10/80-9/81 only.

c = Flow data summed for the following major tributaries: North Fork Stillaguamish at Arlington, 1928-1980; South Fork Stillaguamish at Granite Falls, 1928-1980; Pilchuck Creek at Bryant, 1930, 1931, 1951, 1953-1975. Water quality data taken at Silvana, downstream from the above gages.

d = Flow data taken at Monroe, above the confluence of the Pilchuck River; no flow averages exist for Pilchuck River.

e = 10/76-9/77 and 10/80-9/81 only.

f = Curl (1982).

g = Water quality data taken at Allentown Bridge, approximately 6.8 km downstream from Tukwilla. Water quality data for 7/80-9/81 only.

h = Averages for 7/80-9/81.

i = Water quality data taken at Nisqually, approximately 29 km downstream from McKenna. Water quality data do not include the 10/76-9/77 period.

j = Water quality data taken at Tumwater, approximately 37 km downstream from Rainier. Water quality data do not include the 10/80-9/81 period.

k = 10/76-9/77 only.

l = Water quality data do not include the 10/76-9/77 and 10/80-9/81 periods.

m = Water quality data do not include the 10/76-9/77 period.

n = 1971 and 1974 only.

o = 7/80-9/81 only.

p = 10/78-5/81 only.

q = 10/77-9/80 only.

Table 4-2. Cities in the Study Area With Combined Storm and Wastewater Sewers Draining Directly into Marine Waters

City	Marine Receiving Water for CSOs
Anacortes	Guemes Channel and Fidalgo Bay
Bellingham	Bellingham Bay
Blaine	Drayton Harbor (Strait of Georgia)
Bremerton	Sinclair Inlet
Everett	Port Gardner (Whidbey Basin)
Marysville	Possession Sound (Whidbey Basin)
Seattle Metropolitan Area	Elliott Bay and Central Basin
Olympia	Budd Inlet (Southern Puget Sound)
Port Angeles	Port Angeles Harbor (Strait of Georgia)

Atmospheric Sources

Pollution loading to Puget Sound from the atmosphere occurs by one of three processes: gaseous exchange, dry fall, and wet fall. Gaseous exchange leads to the equilibration of a substance between air and water. The distribution between air and water compartments is a function of the vapor pressure and the water concentration of the substance; flux of a pollutant into Puget Sound occurs when the vapor pressure is greater than the equivalent dissolved concentration in the water. Dry fall is the deposition of particulate matter primarily due to gravity. The sources of the particulate matter can be natural or anthropogenic. The term wet fall applies to the flux of pollutants in both dissolved and particulate form in precipitation falling directly into Puget Sound. Both dry and wet fall on adjacent lands may be transported to Puget Sound in surface runoff.

Erosion

Wave and tidal action cause continuous erosion of the coastal lands of Puget Sound. Rivers transport materials eroded from the watershed and are included in the riverine pollutant loading. Shoreline erosion along Puget Sound is a nonpoint source of pollutants. The soils contain natural pollutants (mostly particulates, metals, and nutrients), but also some anthropogenic pollutants that contribute to the mass loading.

Dredging and Filling

Dredging or filling activities constitute pollutant sources when dredge spoils or fill material from outside the study area are deposited in Puget Sound. Dredging and disposal within Puget Sound does not create additional loadings to the Sound as a whole, but may remobilize pollutants or redistribute pollutants between subareas of Puget Sound. Dredging and spoils disposal are important factors in pollutant distribution, availability, and fate. Furthermore, dredging and fill operations may alter habitat directly or through changing current patterns, which may have a significant impact on the distribution and fate of pollutants.

Water Circulation (Advection)

Movement of materials from one water mass to another because of water circulation is referred to as advection. Waters flowing into Puget Sound from the Straits of Juan de Fuca and Georgia transport pollutants which add to the pollutant loading. Water and pollutant circulation within Puget Sound does not add to the pollutant loading of Puget Sound as a whole, but is of concern during the study of smaller water masses within Puget Sound.

Other Categories of Sources

Other pollution sources include but are not limited to spills, groundwater movement into Puget Sound, navigational activities, recreational activities, natural biological inputs from resident fish and wildlife, and random illegal discharges. Mass loading from these sources is unpredictable or exceedingly difficult to quantify.

Point Source vs. Nonpoint Source Pollution

Nonpoint source pollution is gaining nationwide prominence in water quality issues as point source pollution is brought under control through the NPDES program. This trend is also observed in Washington. Twenty-six of the Water Resource Inventory Area (WRIA) segments in western Washington fail to meet water quality goals because of point or nonpoint source problems (WDOE 1983). Of these, 73 percent are affected predominately by nonpoint sources. Most segments affected by point source problems are located in the Puget Sound vicinity. These include inner Commencement Bay to Puyallup River Mile 1, Commencement Bay, Port Gardner and inner Everett Harbor, and the Duwamish Waterway and River, although a recent study by Harper-Owes (1983) suggests that this latter segment experiences greater pollutant loading from nonpoint sources. Segments classified as failing to meet water quality goals due to nonpoint sources include Elliott Bay. Budd Inlet is classified as a segment in which water quality goals are not attainable due to natural or irreversible causes.

Extent and Nature of Mass Loading Data

Sources of Mass Loading Data

Mass loading data have been collected by different people and organizations for many different reasons; therefore, it is not surprising to note that mass loading data described below are incomplete or rarely consistent. Sampling methodology, spatio-temporal distribution of sampling effort, presentation of the results and data storage format are as diverse as the agencies and purposes for obtaining these data.

WDOE NPDES Permit Application Files. WDOE maintains in the Lacey headquarters office a complete file of the NPDES permits issued in Washington. The Redmond and Tumwater regional WDOE offices also have files on dischargers in their respective regions. The files are kept alphabetically by county and city and are open to the public. A permit file normally contains a copy of the permit, the permit application, correspondence related to the permit, and old permits. Information on the permit which is applicable to mass loading includes location of

the discharge, type of discharger, character of the discharge, limits placed on the discharge, and monitoring requirements. The permit application may contain limited information on the chemical composition of the discharge, but in most cases is outdated. This information is useful but requires significant time to extract the data.

NPDES Discharge Monitoring Reports (DMR). DMRs are periodic reports required by the NPDES permits. These reports are located at the appropriate regional WDOE office and are also kept alphabetically by county and city. These files are open to the public. The frequency of submittal of these reports is stated in the permit requirement. Monthly, quarterly, and annual reports are common. The reports contain information required in the permit conditions. The DMR files are often incomplete due to missing reports (not submitted or lost). In some cases the permittee's monitoring requirements are not fulfilled in the DMR.

WDOE Industrial Discharger Files. WDOE maintains files in Lacey on a group of industrial dischargers including pulp mills, oil refineries, and smelters. These files are open to the public and are kept alphabetically. Included in these files are NPDES renewal applications with effluent discharge data, DMRs, and inspection results. The files tend to be up-to-date and complete.

River Monitoring Reports. The WDOE regional office in Tumwater has recorded on computer files the results of the river monitoring program. A complete listing of the data base for Washington has recently been printed and is available for review at the Tumwater office. Computer access is also a possibility. Several rivers are monitored on a regular basis for a variety of parameters which can include:

- Hydrological data
- Conventional parameters
- Extended conventional parameters
- Heavy metals
- Other metals and salts
- Pesticides

The data are summarized annually and cumulatively and, until recently, were published as part of the USGS Water Resources Data Summaries for Washington (USGS 1978). Only major rivers are included in the monitoring program and no information is collected regularly on the numerous small streams. The monitoring stations are sometimes located several miles upstream from the river mouth.

NPDES Inspections, Class II. WDOE conducts permit compliance inspections of NPDES-permitted dischargers. As discussed in Chapter 2, four classes of compliance inspections exist. A

Class II inspection analyzes effluent samples, and these results are available at WDOE regional office at Tumwater. The annual State/EPA Agreement lists the NPDES-permitted dischargers which are to be inspected in the agreement year. The analysis performed varies but can include parameters not included on the permit. Receiving water quality data may also be gathered concurrently and included in the inspection report.

EPA Permit Compliance Files. EPA has a computer file of data gathered for evaluating permit compliance of the major dischargers. A computer printout can be obtained from the Seattle EPA office. DMRs are the original information source for this file. The data include permit conditions and actual reported measurements. Several dischargers are not included in the file, even though they are indicated as major dischargers in WDOE files.

Metro Treatment Plant Monitoring Records. Metro conducts monitoring programs on the outfalls for its five wastewater treatment plants. These monitoring results are often presented in report documents which are distributed to several libraries. The information presented varies as a function of the original purpose of the monitoring program.

Metro River Monitoring Data. WDOE has delegated to Metro the monitoring program for the rivers within Metro's service area. The data are stored on computer files and are available from Metro. Some documents have been prepared from the data and are available at most agency and certain local libraries. The data collected are very similar to the data collected by WDOE outside of the Metro service area.

Metro CSO Monitoring Data. Metro has collected flow measurements through computer monitoring of the CSOs in its system. A report (Metro 1980) was produced which covers mainly CSO input to Lake Washington, but it also includes one Puget Sound CSO at Denny Way. Data collected on a regular basis are mainly concerned with discharge rates.

Metro Urban Runoff Data. Metro, the City of Bellevue, the USGS, and the University of Washington are currently involved in a national urban runoff program. Program reports from Bellevue and USGS are not available at this time. Metro's report (Galvin and Moore, 1982) was reviewed as part of this study. Metro's role in the program was to identify priority pollutants and other toxicants in urban runoff and other nonpoint sources, and evaluate best management practices (BMPs) for their control. Analysis of runoff from two Bellevue sites was a major portion of this project.

NOAA Ocean Water Quality Data. NOAA, through its MESA program, has collected a significant amount of information on Puget Sound. Reports have been distributed to several local and agency libraries. Most of these data address issues other than

mass loading. The National Environmental Satellite, Data, and Information Service (NESDIS) maintains computerized files of marine water quality data collected by various researchers. The data are contributed on a voluntary basis and comprise a global network of water quality monitoring stations. Water quality data gathered outside of the study area may be used in estimating the pollutant loading resulting from advection between the Pacific Ocean, the Straits, and Puget Sound.

WDOE Marine Water Monitoring Program. WDOE conducts water quality monitoring at surface and 10m depths at 44 stations within the study area (Figure 4-1) on a monthly basis during the spring, summer, and fall. Marine water is not monitored during the winter months. The parameters monitored are listed in Table 4-3. Some variation between stations exists; parameters analyzed at only a few sites are indicated by parentheses, along with the number of stations where monitoring of these parameters occurs. The data are stored in computer files and are kept at the WDOE regional office in Tumwater. Annual and cumulative summaries are also included in the data base. The data can be used for computing the pollutant loading resulting from water flux from one local water mass to another.

Table 4-3. Parameters Monitored at WODE Marine Stations. Parameters Monitored at All Stations Unless Noted in Parentheses

temperature	nitrate	
dissolved oxygen	nitrite	
Secchi disk	ammonia	
fecal coliform	orthophosphate	
turbidity	total phosphate	
salinity	sulfite waste liquor	(8)
specific conductivity	total organic carbon	(4)
pH	chlorophyll *a*	(4)
	arsenic	(1)

EPA 301(h) Waiver Applications. The CWA allows municipal wastewater treatment plants that discharge into marine waters to apply for a waiver from secondary treatment requirements. Twenty-nine dischargers in the study area have tentatively applied for the waiver (Table 4-4). The application from major dischargers must include a section on conventional parameters and priority pollutant composition of the discharge. The data collected to comply with this requirement are not readily accessible to the general public until after a tentative decision on the application has been made. The data were made available for this project and have been utilized only to determine mass loading for subareas within Puget Sound (Appendix D). This program will yield mass loading data in the future from those dischargers that are granted the waiver.

Table 4-4. Municipal Dischargers in the Study Area Submitting Section 301(h) Waiver Applications*

Municipal Discharger	Annual Mean Flow in MGD		Receiving Water	Regional Water Body
	Limit	Reported		
Anacortes - Main	-	1.4	Guemes Channel	Rosario Strait
Anacortes - Skyline	-	0.09	Burrows Bay	Rosario Strait
Bellingham	18.0	12.0	Bellingham Bay	Strait of Georgia
Coupeville	0.125	0.12	Penn Cove	Whidbey Basin
Des Moines	5.0	3.4	Puget Sound	Central Basin
Edmonds	5.0	5.6	Puget Sound	Central Basin
Everett	9.9	9.9	Snohomish River	Whidbey Basin
Lakehaven Sewer District - Lakota	6.7	2.1	Dumas Bay	Central Basin
Lakehaven Sewer District - Redondo	3.2	1.6	Poverty Bay	Central Basin
Langley	-	0.045	Saratoga Passage	Whidbey Basin
Lynnwood	-	3.0	Puget Sound	Central Basin
Manchester	-	0.07	Puget Sound	Central Basin
Mason County - Hartstene Pt.	0.056	-	Case Inlet	Southern Puget Sound
Mukilteo	0.25	-	Possession Sound	Whidbey Basin
Penn Cove	0.06	0.05	Penn Cove	Whidbey Basin
Port Angeles	4.8	3.29	Port Angeles Harbor	Strait of Juan de Fuca
Port Townsend	1.2	1.0	Strait of Juan de Fuca	Strait of Juan de Fuca
Seattle - Alki	15.0	6.6	Puget Sound	Central Basin
Seattle - Carkeek	-	3.0	Puget Sound	Central Basin
Seattle - Richmond	3.2	1.8	Puget Sound	Central Basin
Seattle - West Point	125.0	125.0	Puget Sound	Central Basin
Skagit County Sewer District No. 1	0.06	-	Skagit Bay	Whidbey Basin
Southwest Suburban Sewer District - Miller	4.25	2.6	Puget Sound	Central Basin
Southwest Suburban Sewer District - Salmon	3.5	3.0	Puget Sound	Central Basin
Steilacoom	0.77	0.78	Puget Sound	Southern Puget Sound
Tacoma - Central	78.0	24.6	Puyallup River	Central Basin
Tacoma - North End	10.0	5.9	Commencement Bay	Central Basin
Tacoma - Western Slope	3.0	2.1	The Narrows	Southern Puget Sound
Westside Water District	-	0.45	The Narrows	Southern Puget Sound

*As of July 1, 1983.

Applicability of the Data Source

Table 4-5 summarizes the general usefulness of the various categories of data described in the preceding section. Although the information presented in Table 4-5 will help to expedite a search for needed mass loading data, it should be noted that variability occurs within each category, e.g., some 301(h) waiver applications provide detailed information on priority pollutants in the effluent, whereas other applications currently do not. This variation tends to be minimized in the type of overview presented in Table 4-5. The entries in Table 4-5 are as follows:

- Pollutant coverage - The groups of pollutants defined in the introduction to this chapter are used to characterize the parameters which were measured for the data base, where:

  conv = conventional water quality
  ext conv = extended conventional water quality parameters
  pri poll = entire priority pollutant list
  h metals = heavy metal pollutants
  other = other pollutants measured with descriptive footnote at bottom of Table 4-5.

- Monitoring frequency - The typical time scale is listed here: monthly, seasonal, biannual, and annual. If no period is appropriate for the data base, a descriptive term is used where appropriate.
- Sample collection - The method of sample collection is given as "grab", "composite", or "both". A grab sample is collected at a single instant from the discharge flow. A composite sample is collected by taking small samples from the discharge flow over a period of time and mixing these together to form the sample. Occasionally both techniques are used.
- Duration of record - For programs that collect data periodically, an indication is given as to how long the program has existed. For nonperiodic programs, no indication is given.
- Station location - The location of data collection is given as a subarea if limited to a geographical region.
- Data format - The data may be in raw form in files, in computer files, or in draft or published reports. This descriptor characterizes how readily the quantitative data may be accessed and incorporated into mass loading calculations.
- Consideration of transport and fate processes - This entry notes whether data were collected on the subsequent transport or fate of the pollutants in the effluent.
- Applicability - The usefulness of the data base for mass loading information is noted.

Table 4-5. Characterization of Various Sources of Mass Loading Data for Puget Sound

Data Base/ Criteria	NPDES Permit Files	Industrial NPDES Discharge Monitoring Reports	Municipal NPDES Discharge Monitoring Reports	WDOE Industrial Discharger Files	WDOE Class II Inspections	EPA, NPDES Permit Compliance	WDOE Marine Water Monitoring
Pollutant coverage	Conv.	Conv.	Conv. Ext. conv.	Conv. Ext. conv. Pri. poll. Other*	Conv. (Pri. poll for Commencement Bay)	Conv. (NPDES DMR information)	Conv. Ext. conv.
Monitoring frequency	Once	Monthly	Monthly	Once	As designated in state/EPA agreement	Monthly	Monthly for nonwinter season
Duration of record		Since issuance of permit	Since issuance of permit			Since issuance of permit	Several years
Sample collection	Composite and grab	Composite and grab	Composite	Composite	Composite and grab	Composite and grab	Grab
Location of stations	At discharge point	At discharge point	At discharge point	At discharge point	At discharge point, (some ambient near discharge)	At discharge point	Mid-channel Puget Sound
Data format	Raw in files	Raw in files	Raw in files	Filed on EPA Form 3510-2C	Inspection reports	Computer files, not all NPDES dischargers included	Computer files, with annual computerized summaries
Consideration of transport and fate processes	No	No	No		No (yes for Commencement Bay)	No	
Applicability	Locations, discharger characteristics, very little pollutant data	Good for conv. loadings, some individual DMRs are more informative	Good for conv. loadings and ext. conv., some coverage of h. metals	Good for pollutants covered	Often contains more information than required on NPDES permit	No new information but does computerize discharges	Useful for calculating advection between water masses

* As listed on EPA Form 3510-2C

Table 4-5. Cont'd.

Data Base/ Criteria	WDOE River Monitoring	Metro River Monitoring	Metro Treatment Plant Monitoring	Metro, CSO Monitoring	Metro Urban Runoff	NOAA NESDIS Ocean Water Quality**	EPA 301(h) Applications
Pollutant coverage	Conv. Ext. conv. H. metals Other	Conv. Ext. conv.	Conv. Ext. conv. Pri. poll.	(Flow only) (Conv. h. metals for Denny Way)	Conv. Ext. conv. Pri. poll.	Highly variable	Conv. Pri. poll.
Monitoring frequency	Monthly, some only once	Monthly			Storm events during study period	Highly variable	Once***
Duration of record	Several years	Several years			Oct 75-Dec 76 Oct 80-Jan 82	Highly variable	
Sample collection	Grab	Grab	Composite		Composite		Composite
Location of stations	Near large river mouths	Metro service area	Metro treatment plants	Metro service area	Seattle Metropolitan area	Puget Sound and Straits	Municipal discharge points
Data format	Computer files, with annual computerized summaries	Computer files			Published and draft reports	Data from many investigators stored in computer files	Waiver application
Consideration of transport and fate processes	No	No			Yes	No	No
Applicability	Good for pollutant loading from large rivers	Good for pollutant loading from rivers in Metro service area	Good data for West Point discharge	Very little data	Good for Elliott Bay, could be applied to Puget Sound	Useful for calculating advection between water masses	Pri. poll. data, limited to only a few municipal dischargers

**Data contributed by various research projects and submitted to NESDIS for computer filing.
***Wet and dry season for larger dischargers.

Summary of Available Mass Loading Values

One of the objectives of this report, as described in Chapter 1, is to describe what is known about mass loading of pollutants to Puget Sound. This task is needed to initiate the process of linking pollutant loading to adverse impacts on beneficial uses. Based on the preceding review of the data base, it is readily apparent that the data base is incomplete and that certain loading sources are more poorly documented than others.

Matrices that summarize the availability of information for each type of loading source in various subareas of Puget Sound were developed. These matrices summarize how much is currently known about mass loading of certain pollutants from the designated sources. The ratings do not indicate whether the pollutant is found discharging into the water body. The qualitative ratings of mass loading data by source for various areas of Puget Sound are presented in Tables 4-6 to 4-18. The ratings are heavily dependent on the ratio between the number of dischargers with mass loading data and the total number of dischargers in the specific area, and the ratio between the volume of discharge providing mass loading data and the total volume of the discharge in the specific area. The quality of mass loading data is not a major consideration in the rating.

Each table rates the mass loading data available for each pollutant (or pollutant group) by source for a specific area. The study area is segregated by region and subarea (Figure 1-2). The subareas were selected as localized water bodies in which separate mass loading values would be of use to water quality managers. Although these subareas are located in certain regions of Puget Sound, the ratings for the subareas are not included in the ratings for the region. To present the information in an efficient manner, without significant loss of detail, the pollutants have been grouped where possible. Five rating categories were developed: excellent, good, fair, poor, and no rating. If no data exist, no rating is provided in the tables. Hyphens are used to identify cases in which data are not needed.

The table for Central Puget Sound (Table 4-6) has an additional column for Metro's West Point treatment plant due to the sheer volume discharged from this point source. A yes or no is given if the pollutant has or has not been looked for in the effluent. Several studies concerning mass loading to Central Puget Sound are ongoing and may provide information to update this table and the Elliott Bay table (Table 4-8) in the near future.

Actual values of known mass loadings to Puget Sound are found in Appendix D. Because of the quality of the data base for these calculated values, it is imperative that the reader note that these values are at best tentative. Several studies

are underway which may allow recalculation of values for the Central Basin in the near future.

Summary

Mass loading data provide part of the basis for decision making, but impacts of a discharge (or its removal) can only be determined when the contribution of the discharge is viewed with respect to the cumulative discharges and processes affecting the receiving water mass. Pollution sources may be natural, anthropogenic or, in the case of river input, a mixture of both. The sources are controllable to varying degrees but, until recently, focus has generally been placed on control of anthropogenic point sources. It is important not only to quantify the relative loading of a source, but also to determine the relative degree of control which can be exerted over it so that cleanup efforts can be focused on sources for which it is most cost-effective.

Major sources of pollutant loading include NPDES-permitted discharges, combined sewer overflows, stormwater runoff, atmospheric fallout, dredge-and-fill activities, rivers and streams, advection, and erosion. Available sources of mass loading data and the quality of the data are assessed for the major areas of Puget Sound. Data are available primarily for point sources, because they are controlled by permits and require discharge monitoring. Conventional and extended conventional water quality parameters comprise the bulk of the available data; with the exception of heavy metals, information on most of the priority pollutants is often limited to a few analyses. Information on other toxicants which are not considered of sufficient national priority to be listed as EPA priority pollutants (e.g., CBDs) is almost nonexistent.

Loading for nonpoint sources is not documented, partly because nonpoint discharges are not permitted sources, but primarily because their diffuse nature does not easily lend itself to source identification and/or monitoring. Estimates of mass loading for a few pollutants have been made for such nonpoint sources as erosion and atmospheric input, but the estimated inputs vary widely by researcher, depending on the assumptions used. The relative contribution of nonpoint pollution sources to Puget Sound is expected to increase as permit programs bring point source discharges increasingly into compliance with water quality standards and objectives.

In general, mass loading data for Puget Sound are not readily available. Municipal dischargers have been most extensively studied, but the data are often limited to conventional water quality parameters.

Table 4-6. Availability of Toxicant Loading Data for Sources Discharging into Central Puget Sound*

Source/Pollutant	Municipal	Industrial	CSO	Surface Runoff	River	Atmospheric	Erosion	Water Circulation	West Point STP
PRIORITY POLLUTANTS									
Antimony	Fair	Poor							Yes
Arsenic	Poor	Poor					Good		Yes
Asbestos	Fair	Poor							Yes
Beryllium	Fair	Poor							Yes
Cadmium	Fair	Fair							Yes
Chromium	Fair	Fair							Yes
Copper	Fair	Fair			Poor		Good	Good	Yes
Cyanide	Fair	Fair							Yes
Lead	Fair	Poor			Poor		Good	Good	Yes
Mercury	Fair	Poor							Yes
Nickel	Fair	Fair			Poor				Yes
Selenium	Poor	Poor							Yes
Silver	Poor	Poor							Yes
Thallium	Poor	Poor							Yes
Zinc	Fair	Fair			Poor		Good	Good	Yes
Pesticides, PCBs & related compounds	Fair	Poor							Yes
Halogenated aliphatic hydrocarbons	Fair	Poor							Yes
Halogenated ethers	Fair	Poor							Yes
Monocyclic aromatics	Fair	Poor							Yes
Pthalate esters	Fair	Poor							Yes
Polycyclic aromatic hydrocarbons	Fair	Poor							Yes
Nitrosamines and misc. compounds	Fair	Poor							Yes
EXTENDED CONVENTIONAL POLLUTANTS									
Flow	Excel.	Good			Poor	-	-		Yes
BOD	Excel.	Fair							Yes
COD	Poor	Poor							No
Total solids	Poor	Poor							No
TNVS	Poor	Poor							No
TSS	Excel.	Fair				-			Yes
TNVSS	Poor	Poor				-			No
Total nitrogen	Poor	Poor							No
Total phosphorus	Poor	Poor							No
Oils and grease		Fair				-			No
pH	Excel.	Excel.							Yes
Fecal coliform	Excel.	Fair				-			Yes

* Several loading studies are in progress. Metro TPPS will provide additional data. Data for local embayments (Elliott Bay, Commencement Bay, Sinclair Inlet) are not included.

Table 4-7. Availability of Toxicant Loading Data for Sources Discharging into Commencement Bay

Source/Pollutant	Municipal	Industrial	CSO*	Surface Runoff	River	Atmospheric	Erosion	Water Circulation
PRIORITY POLLUTANTS								
Antimony		Poor	-					
Arsenic	Excel.	Fair	-		Good		Poor	
Asbestos	Excel.		-					
Beryllium			-					
Cadmium	Excel.	Fair	-		Good			
Chromium	Excel.	Fair	-		Good			
Copper	Excel.	Fair	-		Good		Poor	
Cyanide		Fair	-					
Lead	Excel.	Fair	-		Good		Poor	
Mercury	Excel.	Fair	-		Good			
Nickel	Excel.	Fair	-		Good			
Selenium	Excel.	Poor	-		Good			
Silver	Excel.	Poor	-		Good			
Thallium			-					
Zinc	Excel.	Fair	-		Good		Poor	
Pesticides, PCBs & related compounds		Poor	-					
Halogenated aliphatic hydrocarbons		Fair	-					
Halogenated ethers	Fair	Fair	-					
Monocyclic aromatics	Fair	Fair	-					
Pthalate esters		Fair	-					
Polycyclic aromatic hydrocarbons	Good	Fair	-					
Nitrosamines & misc. compounds	Fair	Fair	-					
EXTENDED CONVENTIONAL POLLUTANTS								
Flow	Excel.	Good	-		Good	-	-	
BOD	Excel.	Fair	-					
COD	Fair	Poor	-		Good			
Total solids	Fair	Fair	-					
TNVS	Fair	Fair	-					
TSS	Excel.	Fair	-		Good	-		
TNVSS	Fair	Fair	-			-		
Total nitrogen	Fair	Fair	-		Good			
Total phosphorus	Fair	Fair	-		Good			
Oils & grease	Fair	Fair	-			-		
pH	Excel.	Fair	-		Good			
Fecal coliform	Excel.		-		Good	-		

*No CSOs in Commencement Bay.

Table 4-8. Availability of Toxicant Loading Data for Sources Discharging into Elliott Bay*

Source/Pollutant	Municipal*	Industrial	CSO**	Surface Runoff	River**	Atmospheric	Erosion	Water Circulation
PRIORITY POLLUTANTS								
Antimony	-				Good			
Arsenic	-				Good		Poor	
Asbestos	-							
Beryllium	-				Good			
Cadmium	-	Poor			Good			
Chromium	-	Poor			Good			
Copper	-	Poor	Poor	Good	Good		Poor	
Cyanide	-							
Lead	-	Poor	Poor	Good	Good		Poor	
Mercury	-		Poor		Good			
Nickel	-	Poor			Good			
Selenium	-				Good			
Silver	-	Poor			Good			
Thallium	-				Good			
Zinc	-	Poor	Poor	Good	Good		Poor	
Pesticides, PCBs & related compounds	-		Poor		Good			
Halogenated aliphatic hydrocarbons	-				Good			
Halogenated ethers	-				Good			
Monocyclic aromatics	-				Good			
Pthalate esters	-				Good			
Polycyclic aromatic hydrocarbons	-				Good			
Nitrosamines & misc. compounds	-				Good			
EXTENDED CONVENTIONAL POLLUTANTS								
Flow	-	Fair	Poor		Good	-	-	
BOD	-	Poor						
COD	-	Poor						
Total solids	-	Poor						
TNVS	-	Poor						
TSS	-	Poor	Poor		Good	-		
TNVSS	-	Poor				-		
Total nitrogen	-	Poor			Good			
Total phosphorus	-	Poor	Poor		Good			
Oils & grease	-	Poor	Poor			-		
pH	-	Fair			Good			
Fecal coliform	-	Poor			Good	-		

*No municipal discharges to Elliott Bay.
**Several loading studies are in progress; Metro TPPS report may provide some data.

Table 4-9. Availability of Toxicant Loading Data for Sources Discharging into Sinclair Inlet

Source/Pollutant	Municipal	Industrial	CSO	Surface Runoff	River	Atmospheric	Erosion	Water Circulation
PRIORITY POLLUTANTS								
Antimony								
Arsenic							Poor	
Asbestos								
Beryllium								
Cadmium	Fair							
Chromium	Fair							
Copper	Fair							
Cyanide	Fair							
Lead	Fair						Poor	
Mercury								
Nickel	Fair							
Selenium								
Silver								
Thallium								
Zinc	Fair							
Pesticides, PCBs & related compounds								
Halogenated aliphatic hydrocarbons								
Halogenated ethers								
Monocyclic aromatics								
Pthalate esters								
Polycyclic aromatic hydrocarbons								
Nitrosamines & misc. compounds								
EXTENDED CONVENTIONAL POLLUTANTS								
Flow	Excel.	Excel.				-	-	
BOD	Excel.							
COD	Excel.							
Total solids	Excel.							
TNVS	Excel.							
TSS	Excel.					-		
TNVSS	Excel.					-		
Total nitrogen	Excel.							
Total phosphorus	Excel.							
Oils & grease		Excel.				-		
pH	Excel.	Excel.						
Fecal coliform	Excel.					-		

Table 4-10. Availability of Toxicant Loading Data for Sources Discharging into Southern Puget Sound *

Source/Pollutant	Municipal	Industrial	CSO**	Surface Runoff	River	Atmospheric	Erosion	Water Circulation
PRIORITY POLLUTANTS								
Antimony		Poor	-					
Arsenic	Poor	Poor	-		Fair		Good	
Asbestos	Poor		-					
Beryllium		Poor	-					
Cadmium	Poor	Poor	-		Fair			
Chromium	Poor	Poor	-		Fair			
Copper	Poor	Poor	-		Fair		Good	
Cyanide		Poor	-					
Lead	Poor	Poor	-		Fair		Good	
Mercury	Poor	Poor	-		Fair			
Nickel	Poor	Poor	-		Fair			
Selenium	Poor	Poor	-		Fair			
Silver	Poor	Poor	-		Fair			
Thallium		Poor	-					
Zinc	Poor	Poor	-		Fair		Good	
Pesticides, PCBs & related compounds		Poor	-					
Halogenated aliphatic hydrocarbons		Poor	-					
Halogenated ethers	Poor	Poor	-					
Monocyclic aromatics	Poor	Poor	-					
Phthalate esters		Poor	-					
Polycyclic aromatic hydrocarbons	Poor	Poor	-					
Nitrosamines & Misc. compounds	Poor	Poor	-					
EXTENDED CONVENTIONAL POLLUTANTS								
Flow	Good	Good	-		Good	-	-	
BOD	Excel.	Fair	-					
COD	Fair	Poor	-		Fair			
Total solids	Poor		-					
TNVS	Poor		-					
TSS	Good	Fair	-		Fair	-		
TNVSS	Poor		-			-		
Total nitrogen	Fair	Poor	-		Good			
Total phosphorus	Fair	Poor	-		Good			
Oils & grease	Poor	Poor	-			-		
pH	Excel.	Fair	-		Good			
Fecal coliform	Good	Poor	-		Good	-		

*Data for Budd Inlet not included.
**CSO in Budd Inlet only.

Table 4-11. Availability of Toxicant Loading Data for Sources Discharging into Budd Inlet

Source/Pollutant	Municipal	Industrial	CSO	Surface Runoff	River	Atmospheric	Erosion	Water Circulation
PRIORITY POLLUTANTS								
Antimony								
Arsenic							Poor	
Asbestos								
Beryllium								
Cadmium								
Chromium								
Copper								
Cyanide								
Lead								
Mercury								
Nickel								
Selenium								
Silver								
Thallium								
Zinc								
Pesticides, PCBs & related compounds								
Halogenated aliphatic hydrocarbons								
Halogenated ethers								
Monocyclic aromatics								
Phthalate esters								
Polycyclic aromatic hydrocarbons								
Nitrosamines & Misc. compounds								
EXTENDED CONVENTIONAL POLLUTANTS								
Flow	Excel.				Good	-	-	
BOD	Good							
COD	Good							
Total solids								
TNVS						-		
TSS	Excel.					-		
TNVSS								
Total nitrogen	Good				Good			
Total phosphorus	Good				Good			
Oils & grease						-		
pH	Good				Good			
Fecal coliform	Good				Good	-		

Table 4-12. Availability of Toxicant Loading Data for Sources Discharging into Whidbey Basin*

Source/Pollutant	Municipal	Industrial	CSO	Surface Runoff	River	Atmospheric	Erosion	Water Circulation
PRIORITY POLLUTANTS								
Antimony								
Arsenic								
Asbestos							Good	
Beryllium								
Cadmium								
Chromium								
Copper					Good			
Cyanide					Good		Good	
Lead								
Mercury					Good		Good	
Nickel					Good			
Selenium								
Silver								
Thallium								
Zinc								
Pesticides, PCBs & related compounds					Good		Good	
Halogenated aliphatic hydrocarbons								
Halogenated ethers								
Monocyclic aromatics								
Pthalate esters								
Polycyclic aromatic hydrocarbons								
Nitrosamines & misc. compounds								
EXTENDED CONVENTIONAL POLLUTANTS								
Flow	Excel.	Good			Good	-	-	
BOD	Good							
COD	Fair							
Total solids	Fair							
TNVS	Fair							
TSS	Good	Fair				-		
TNVSS	Fair					-		
Total nitrogen	Fair				Good			
Total phosphorus	Fair				Good			
Oils & grease		Fair				-		
pH	Excel.	Fair			Good			
Fecal coliform	Excel.				Good	-		

*Data for Port Gardner not included.

Table 4-13. Availability of Toxicant Loading Data for Sources Discharging into Port Gardner

Source/Pollutant	Municipal	Industrial	CSO	Surface Runoff	River	Atmospheric	Erosion	Water Circulation
PRIORITY POLLUTANTS								
Antimony		Fair						
Arsenic		Fair					Poor	
Asbestos		None						
Beryllium		Fair						
Cadmium		Fair			Good			
Chromium		Fair			Good			
Copper		Fair			Good		Poor	
Cyanide		Fair						
Lead	Poor	Fair			Good		Poor	
Mercury		Fair			Good			
Nickel	Poor	Fair			Good			
Selenium		Fair			Good			
Silver	Poor	Fair			Good			
Thallium		Fair			Good			
Zinc	Poor	Fair			Good		Poor	
Pesticides, PCBs & related compounds		Fair						
Halogenated aliphatic hydrocarbons		Fair						
Halogenated ethers		Fair						
Monocyclic aromatics		Fair						
Phthalate esters		Fair						
Polycyclic aromatic hydrocarbons		Fair						
Nitrosamines & misc. compounds		Fair						
EXTENDED CONVENTIONAL POLLUTANTS								
Flow	Excel.	Fair			Good	-	-	
BOD	Excel.	Fair						
COD	Fair	Fair						
Total solids	Fair	Fair						
TNVS		Fair						
TSS	Excel.	Fair			Good	-		
TNVSS		Fair				-		
Total nitrogen	Fair	Fair			Good			
Total phosphorus	Fair	Fair			Good			
Oils & grease		Fair				-		
pH	Excel.	Fair			Good			
Fecal coliform	Excel.	Fair			Good	-		

Table 4-14. Availability of Toxicant Loading Data for Sources Discharging into the Strait of Georgia*

Source/Pollutant	Municipal	Industrial	CSO	Surface Runoff	River	Atmospheric	Erosion	Water Circulation
PRIORITY POLLUTANTS								
Antimony		Good						
Arsenic		Good					Poor	
Asbestos								
Beryllium		Good						
Cadmium		Good						
Chromium		Good						
Copper		Good					Poor	
Cyanide		Good						
Lead		Good					Poor	
Mercury		Good						
Nickel		Good						
Selenium		Good						
Silver		Good						
Thallium		Good						
Zinc		Good					Poor	
Pesticides, PCBs & related compounds		Good						
Halogenated aliphatic hydrocarbons		Good						
Halogenated ethers		Good						
Monocyclic aromatics		Good						
Pthalate esters		Good						
Polycyclic aromatic hydrocarbons		Good						
Nitrosamines & misc. compounds		Good						
EXTENDED CONVENTIONAL POLLUTANTS								
Flow	Excel.	Excel.			Good	-	-	
BOD	Excel.	Good						
COD		Good						
Total solids								
TNVS								
TSS	Excel.	Excel.			Good	-		
TNVSS						-		
Total nitrogen		Good			Good			
Total phosphorus		Fair			Good			
Oils & grease		Good				-		
pH	Excel.	Excel.			Good			
Fecal coliform	Excel.	Good			Good	-		

* Data for Port Angeles Harbor not included.

Table 4-15. Availability of Toxicant Loading Data for Sources Discharging into Port Angeles Harbor

Source/Pollutant	Municipal	Industrial	CSO	Surface Runoff	River	Atmospheric	Erosion	Water Circulation
PRIORITY POLLUTANTS								
Antimony		Fair						
Arsenic		Fair					Poor	
Asbestos								
Beryllium		Fair						
Cadmium		Fair						
Chromium		Fair					Poor	
Copper		Fair						
Cyanide		Fair					Poor	
Lead		Fair						
Mercury		Fair						
Nickel		Fair						
Selenium		Fair						
Silver		Fair						
Thallium		Fair					Poor	
Zinc		Fair						
Pesticides, PCBs & related compounds		Fair						
Halogenated aliphatic hydrocarbons		Fair						
Halogenated ethers		Fair						
Monocyclic aromatics		Fair						
Pthalate esters		Fair						
Polycyclic aromatic hydrocarbons		Fair						
Nitrosamines & misc. compounds		Fair						
EXTENDED CONVENTIONAL POLLUTANTS								
Flow	Excel.	Fair				-	-	
BOD	Good	Fair						
COD		Fair						
Total solids		Fair						
TNVS		Fair				-		
TSS	Good	Fair				-		
TNVSS		Fair						
Total nitrogen		Fair						
Total phosphorus		Fair				-		
Oils & grease		Fair						
pH		Fair				-		
Fecal coliform	Excel.	Fair						

Table 4-16. Availability of Toxicant Loading Data for Sources Discharging into the Waters near Anacortes

Source/Pollutant	Municipal	Industrial	CSO	Surface Runoff	River	Atmospheric	Erosion	Water Circulation
PRIORITY POLLUTANTS								
Antimony	Fair	Good			-			
Arsenic	Fair	Good			-		Poor	
Asbestos	None				-			
Beryllium	Fair	Good			-			
Cadmium	Excel.	Good			-			
Chromium	Excel.	Good			-			
Copper	Excel.	Good			-		Poor	
Cyanide	Excel.	Good			-			
Lead	Excel.	Good			-		Poor	
Mercury	Excel.	Good			-			
Nickel	Excel.	Good			-			
Selenium	Excel.	Good			-			
Silver	Excel.	Good			-			
Thallium	Excel.	Good			-			
Zinc	Excel.	Good			-		Poor	
Pesticides, PCBs & related compounds	Good	Fair			-			
Halogenated aliphatic hydrocarbons	Excel.	Fair			-			
Halogenated ethers	Excel.	Fair			-			
Monocyclic aromatics	Excel.	Fair			-			
Pthalate esters	Excel.	Fair			-			
Polycyclic aromatic hydrocarbons	Excel.	Fair			-			
Nitrosamines & misc. compounds	Excel.	Fair			-			
EXTENDED CONVENTIONAL POLLUTANTS								
Flow	Excel.	Good			-	-	-	
BOD	Excel.	Good			-			
COD		Good			-			
Total solids		Good			-			
TNVS					-			
TSS	Excel.	Good			-	-		
TNVSS					-	-		
Total nitrogen					-			
Total phosphorus					-			
Oils & grease					-	-		
pH	Fair	Good			-			
Fecal coliform	Excel.	Good			-	-		

Table 4-17. Availability of Toxicant Loading Data for Sources Discharging into Bellingham Bay

Source/Pollutant	Municipal	Industrial	CSO	Surface Runoff	River	Atmospheric	Erosion	Water Circulation
PRIORITY POLLUTANTS								
Antimony		Fair						
Arsenic		Fair					Poor	
Asbestos								
Beryllium		Fair						
Cadmium		Fair						
Chromium		Fair						
Copper		Fair					Poor	
Cyanide		Fair						
Lead		Fair					Poor	
Mercury		Fair						
Nickel		Fair						
Selenium		Fair						
Silver		Fair						
Thallium		Fair						
Zinc		Fair					Poor	
Pesticides, PCBs & related compounds		Fair						
Halogenated aliphatic hydrocarbons		Fair						
Halogenated ethers		Fair						
Monocyclic aromatics		Fair						
Pthalate esters		Fair						
Polycyclic aromatic hydrocarbons		Fair						
Nitrosamines & misc. compounds		Fair						
EXTENDED CONVENTIONAL POLLUTANTS								
Flow	Excel.	Good			Good	-	-	
BOD	Excel.	Good						
COD		Fair						
Total solids								
TNVS								
TSS	Excel.	Fair			Good	-		
TNVSS						-		
Total nitrogen		Fair			Good			
Total phosphorus		Fair			Good			
Oils & grease		Fair				-		
pH	Excel.	Fair			Good			
Fecal coliform	Excel.	Fair			Good	-		

Table 4-18. Availability of Toxicant Loading Data for Sources Discharging into Hood Canal

Source/Pollutant	Municipal	Industrial	CSO*	Surface Runoff	River	Atmospheric	Erosion	Water Circulation
PRIORITY POLLUTANTS								
Antimony			-					
Arsenic			-				Poor	
Asbestos			-					
Beryllium			-					
Cadmium			-					
Chromium			-		Fair			
Copper			-		Fair		Poor	
Cyanide			-					
Lead			-		Fair		Poor	
Mercury			-		Fair			
Nickel			-					
Selenium			-					
Silver			-					
Thallium			-					
Zinc			-		Fair		Poor	
Pesticides, PCBs & related compounds			-					
Halogenated aliphatic hydrocarbons			-					
Halogenated ethers			-					
Monocyclic aromatics			-					
Pthalate esters			-					
Polycyclic aromatic hydrocarbons			-					
Nitrosamines & misc. compounds			-					
EXTENDED CONVENTIONAL POLLUTANTS								
Flow	Excel.	Good	-		Fair	-	-	
BOD	Excel.	Good	-					
COD			-					
Total solids			-					
TNVS			-					
TSS	Excel.	Good	-			-		
TNVSS			-			-		
Total nitrogen			-		Fair			
Total phosphorus			-		Fair			
Oils & grease			-			-		
pH	Excel.	Good	-		Fair			
Fecal coliform	Excel.	Poor	-		Fair	-		

*No CSOs in Hood Canal.

Chapter 5

CIRCULATION AND DISPERSION MODELS

Introduction

The purpose of this section is to identify, describe, and evaluate existing and ongoing circulation and water quality modeling studies of Puget Sound. An evaluation of other modeling studies outside of Puget Sound is also presented. The model evaluations are directed toward assessing the appropriateness of existing models to meet EPA's objectives of quantifying the waste assimilative capacity of Puget Sound and developing meaningful waste management strategies. Circulation and dispersion models play a major role in identifying and describing the processes by which pollutants are distributed in Puget Sound.

EPA requires model formulations and methodologies to evaluate the fate of pollutants within the region. These formulations must be capable of predicting pollutant concentrations which vary spatially and with time. The pollutant classes of primary importance during a discussion of transport and fate processes are:

1. Conservative pollutants - Substances that do not break down or change form; i.e., mass is conserved (example: salinity). Changes in concentration occur by dilution, mixing, transport, and boundary exchange.

2. Nonconservative pollutants - Pollutants that are consumed or produced as a result of physical, chemical, or biological processes (example: ammonia). Pollutants in this class include particles that can settle or position themselves in the water column. Particulates have the ability to absorb other pollutants, acting as a sink for these substances in the upper layers while accumulating them in the sediments. Toxic organic pollutants act as nonconservative substances and their concentrations vary as functions of absorption, evaporation, and decay.

To effectively predict pollutant distributions within Puget Sound, the characteristics of the circulation must be known. Hydrodynamic features such as velocity, flow direction, tidal dispersion, density distributions, and boundary exchange are important in determining pollutant concentrations.

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The remainder of this chapter is divided into five main sections. The first section presents a discussion of the various classes of models and factors considered to be of importance during model reviews. The second section presents reviews of models that have been developed for Puget Sound and consists of two parts. The first part summarizes the model review format, presents an overview of models applied or being applied in the Puget Sound region, and includes a quick reference table of the models reviewed. The second part includes detailed reviews of all existing models and ongoing model development activities which may be potentially relevant to EPA's objectives. The model reviews address the models' objectives, status, and transferability, and provide detailed descriptions of formulations and adequacy. The third section presents reviews of models that have been developed for use elsewhere but could be readily adapted for use in Puget Sound, based on a preliminary model review. The fourth section summarizes the evaluation of the applicability of existing models and/or models under development in meeting EPA's objectives for circulation and dispersion modeling of Puget Sound. The last section describes the data needed to adapt, operate, and calibrate a model for Puget Sound, and explains where many of the data can be found.

Model Evaluation Criteria

Discussion of Model Characteristics

Models are used to represent real life situations in terms that can be easily manipulated and repeated as often as necessary. Most of the models discussed in this report use mathematical formulations to describe the system. Computer programs can be written to provide solutions to these sets of equations. Various techniques can be used to approximate solutions to the representative equations if direct analytical solutions are unavailable or awkward to process.

For this project, circulation models were reviewed to determine applicability to Puget Sound. These models predict the hydrodynamic features of the circulation, which are then used as input to other formulations that predict the transport and dispersion of water quality variables. Model characteristics that must be considered in evaluation include the following:

- Variables and processes modeled
- Validity of theoretical basis for formulations, i.e., assumptions and limitations
- Temporal resolution; i.e., dynamic or steady-state
- Spatial resolution; i.e., grid flexibility and dimensionality; i.e., 1-, 2-, or 3-dimensional treatment
- Previous implementation and verification

o Availability and practical use

The features listed above are discussed briefly below.

Variables and Processes Modeled. In general, processes and variables desired for model representation include hydrodynamic forces (wind, currents, density field, boundary flow exchange, dispersion rates) and water quality variables (salinity, temperature, dissolved oxygen [DO], biochemical oxygen demand [BOD], nutrients, suspended solids, coliform bacteria, and toxic contaminants). Models which include these processes are considered preferentially in the selection procedure.

Theoretical Assumptions and Limitations. The theoretical basis of the model must be examined for soundness. Stated assumptions, simplifications, and limitations inherent in the model development must be evaluated for compatibility with the test area and physical processes of interest. Forcing functions incorporated into the model must be the dominant processes that occur in the prototype. As an example, steady-state mass balance or diffusion-type models lump the effects of tidal flow and mixing into an empirical dispersion coefficient. However, this approach becomes invalid where the detailed circulation is complex in nature (large eddy formations) and controls the ultimate fate of discharged pollutants.

Temporal Resolution. Numerical models treat the physical processes occurring in time either as discrete time steps (dynamic) or as a constant (steady-state). Furthermore, various dynamic models can exhibit time steps ranging from a few seconds to several hours or even days. The approximate time step is generally a function of both the level of sophistication of the numerical technique used, and the length of prototype time desirable for simulation by the model.

Spatial Resolution. The treatment of spatial resolution of calculated variables is a critical aspect in numerical modeling. There is a definite trade-off between spatial resolution required, time step necessitated, and the cost of running the model. Two major factors to be considered include: 1) grid flexibility, and 2) relationship of grid spacing to depth and maximum stable time step. Grid flexibility can be enhanced by using link node or triangular finite element-type models, where areas of interest can be refined and noncritical areas can be more crudely represented. This is also an advantage for models which require larger node spacings in deeper water to avoid unacceptably small time steps. More importantly, the level of sophistication of the numerical integration scheme will determine the allowable maximum stable time step which, in turn, determines the end cost of running the computer program. Highly sophisticated models usually utilize "implicit" integration schemes, as opposed to "explicit" schemes. The implicit schemes are usually more stable and allow the time step to be chosen independently of the grid size and water depth.

Dimensionality. Models can generally be classified as 1-dimensional in the longitudinal, 1-dimensional in the vertical, 2-dimensional in the horizontal, 2-dimensional in the vertical, or 3-dimensional (or layered). The appropriateness of the dimensional treatment of each model depends on the dominant physical processes and geometry of the specific area of interest. The Puget Sound system is very complex and composed of large (wide) deep basins and longitudinally-shaped (thin) deep basins with distinct vertical stratification, as well as irregularly-shaped shallow basins that are vertically well mixed. Thus, most existing models are likely to be limited to only certain portions of Puget Sound. In fact, it may be necessary to "couple" a number of models in order to represent the entire system, if that is desired.

Previous Implementation and Verification. Relatively few numerical models have been rigorously tested on as complex a system as Puget Sound. Successful model comparison to prototype field conditions is highly desirable for any model to be used for predictive purposes. The proper sequence of testing a model involves initial careful adjustment (calibration) of empirical coefficients such as bottom friction, boundary exchange, vertical and horizontal eddy diffusivity, and reaction rates for nonconservative pollutants. Once adjusted, the model is run or "verified" for a specific prototype condition without readjusting the coefficients.

Availability and Practical Use. Many models have been computerized and are available by contacting the appropriate agency. Required computer capacity for models presented in this report varies considerably. Certain computer codes may require modifications for use on available computer resources. Time to implement the computerization of a model and required computer capacity should be considered in the final selection.

Summary of Solution Techniques

There are several solution techniques used in circulation and dispersion model formulations that affect the accuracy, speed, and data required for solution. Methodologies described in the models presented herein include:

Mass Balance. An equation describes a balance between all inputs and all outputs:

$$\text{In-Out} = \text{Change in System}$$

Equations represent a very simplified system.

Partial Differential Equations. The system is represented by a set of partial differential equations which describe the change of one variable with respect to other variables and

conditions as a function of time. These equations may be solved directly or by numerical approximations.

Steady-State. These models do not predict the change in variables with time; rather, these models generate predictions for an infinite (or long-term) time period for a given set of constant inputs.

Finite Difference. This method is used to approximate the solution to a differential equation. The test area is divided into subareas called a grid and the intersections of the grid lines are called nodes. Certain known data (boundary condition values) are used to estimate the initial values for all nodes within the grid. This method normally employs an orthogonal grid system and is most appropriate for regularly shaped water bodies. The grid system is not flexible; however, it is possible to couple a more detailed "nested" model within a cruder large-scale model.

Link-node. The test area is represented by a series of nodes (junctions) and links (channels). A set of 1-dimensional motion equations is written for the links and a set of continuity equations is written for the nodes to fully describe the system. The resulting grid system is extremely flexible in application; however, the hydrodynamic processes are constrained to follow the paths of the linked channels, which is not a true 2-dimensional representation.

Finite Element. This method utilizes an alternative formulation of the differential equations. A corresponding variational principle is used to express the equations as the minimization of an integral. The test region or region of integration is divided into sections called finite elements. The integral assumes a functional form over the entire element and the constants that define the region are selected from the minimization of the integral. Finite element models typically employ triangular-shaped grids, which allows for high flexibility in grid application.

Harmonic Decomposition. For periodic motion in an estuary, the dependent variables in the motion equations may be Fourier decomposed. Decomposition represents the system by the sum of a series of sine or cosine waves with frequencies equal to multiples of a fixed frequency.

Physical Model. The physical model is a scaled-down replica of the waterbody. Dimensional analysis allows the scaling of all variables to reproduce the relationship between the variables as in the prototype. Processes occur in the model as they occur in the prototype with the exception of stated limitations. Physical models of extremely small scale, i.e., the existing Puget Sound model, are more qualitative in nature and can give questionable results for localized phenomena.

Numerical Approximation Methods. Several methods exist for approximating solutions to equations that do not have convenient analytical solutions. Two methods that are used frequently are the Euler and Runge-Kutta approximations. The Euler approximation simply evaluates the differential equation at various time steps starting from an initial known condition. The size of the time step is very important in this method. The Runge-Kutta method also evaluates the differential equation at various time steps but incorporates several other terms in the expression that estimate the parameter for the next time step. These other terms use the value at half-time steps to "adjust" the full time step variable estimation. The Runge-Kutta method approximates curves much more accurately than the Euler method and larger time steps can be used to obtain similar results.

Relationships between variables may also be approximated by a power series. This method uses a sequence of polynomials in the form of a power series to approximate the solution.

Interpolation between existing data is a method of expanding the data base. Known values at certain points are combined to generate a corresponding value at a location where data are unavailable. This procedure usually consists of summing two or more known values multiplied by weighting factors to obtain a value for another nearby location. Models that use this method are commonly called empirical models. Such models are not normally desirable for predictive purposes because they cannot readily project under varying prototype conditions in the absence of appropriate data.

Models Developed for Puget Sound

Model Review Format

The discussion of each model covers the following points:

1. Name of the model.
2. Model objectives.
3. Model description (qualitative).
4. Model formulation - Important equations, assumptions, and resolution capabilities are discussed.
5. Model status - Current stage of model development is considered. Factors such as implementation, verification or calibration, data requirements, and dependence on other models is covered.
6. Model adequacy - The adequacy of the model formulation is considered in relation to the model objectives. Sensitivity with respect to output versus changes in input is discussed.
7. Transferability - Factors, such as data availability, computational requirements, and program accessibility are assessed in terms of the required time and effort to implement the model.

8. Applicability - The degree to which the model meets EPA's objectives in terms of variables and processes modeled, resolution capability, and general applicability.

Brief Model Overview

Table 5-1 displays the comparison of all relevant models in terms of the following model characteristics: variables modeled, solution technique, region modeled, dimensions considered, resolution capabilities, forcing functions, and field application. Figures 5-1 and 5-2 show the areas of Puget Sound that have been modeled on a regional or subarea basis, respectively.

The models presented in Table 5-1 were all developed to achieve different objectives and therefore are not directly comparable. In many cases, certain models can act as supplementary or complementary methodologies to other models.

To provide a basis for comparison, the capability of each model to satisfy EPA's objectives was evaluated. The major emphasis of the evaluation focused on the ability of the models to accurately represent the hydrodynamic processes in Puget Sound. Adequate hydrodynamic models are of primary concern because the ultimate fate and interaction of pollutants discharged from multiple widespread sources is primarily controlled by the often complex temporal and spatial circulation existing in the Sound.

Once an acceptable hydrodynamic model is available, the transport characteristics can be input to models that predict the dispersion, decay, and interaction of biological and chemical constituents. In this regard, important factors for consideration include the capability of the models to accurately describe biological and chemical systems, to predict changes in conservative and nonconservative constituents, to incorporate sedimentation processes such as settling and accumulation rates, and to achieve resolution capacity to adequately detect variations on local (nearfield) and regional (farfield) levels.

Models evaluated in this section have been divided into three main groups: nearfield plume models, transport models, and water quality models. Transport models include those models which attempt to predict circulation characteristics of Puget Sound. Water quality models include models that describe biological and chemical systems and treat the dispersion and transformation of various constituents.

Table 5-1. A Comparison of Water Quality and Circulation Models of Puget Sound and Adjacent Waters

Model Name and Reference	Model Type	Variables Modeled	Area Modeled	Dimensions	Layered	Grid Size	Forcing Functions	Time Scale	Computerized	Field Application
Pollutant Transport (Stewart In preparation)	Plume model, semi-empirical	Aereal extent of plume	Elliott Bay (Duwamish)	2-dimensional	Surface layer	N/A	Wind, gradient, discharge	Unknown	Yes	No
Similarity Solution for Gravitational Circulation (Winter 1973)	Power series	Velocity - vertical and longitudinal, density distribution	Stratified estuaries	2-dimensional horizontal	Surface layer	N/A	Discharge, gradient	Steady state	No	Hood Canal, Central Basin of Puget Sound, Knight Inlet
A Water Budget Study (Friebertshauser and Duxbury 1972)	Mass balance	Mean flux into and out of estuary	Puget Sound	N/A	Two layer	N/A	Inflow, outflow	Monthly or annual	No	Puget Sound
New Approach to Computation of Tidal Motions (Jamart and Winter 1978)	Harmonic decomposition finite element	Velocity, water elevation	Homogeneous estuaries with variable depth	2-dimensional horizontal	No	Variable	Tide, wind	N/A	Yes	Hood Canal
Dynamics of Phytoplankton (Winter et al. 1975)	Finite difference	Chlorophyll a	Puget Sound Central Basin	2-dimensional horizontal	Euphotic zone (surface layer)	0.5 m depth increments	Turbulent mixing discharge, growth/death	0.5 h time step	Yes CDC 6400	Puget Sound Central Basin
Empirical Model for Tidal Currents (Pease 1980)	Interpolation model	Tidal current	Puget Sound, Strait of Juan de Fuca, Strait of Georgia	2-dimensional horizontal	Surface layer	1 km square	Tide, wind	N/A	Yes	Puget Sound
Oceanographic Model (Barnes et al. 1957) and Operating Characteristics of Oceanographic Model (Rattray and Lincoln 1955)	Physical model	Tidal current, dispersion, flushing, salinity	Puget Sound	3-dimensional	No	N/A	Tide, discharge, gradient	Tidal day - equals 76 sec	N/A	Puget Sound
Model of Steady State Salinity (Farmer and Rattray 1963)	Physical model	Salinity distribution	Puget Sound	3-dimensional	No	N/A	Tide, discharge, gradient	Steady state	N/A	No
Effects of Point-Source Discharges in Budd Inlet (Kruger 1979)	Dissolved oxygen model	Dissolved oxygen	Budd Inlet	1-dimensional longitudinal	No	15 segments of variable size	Tide, discharge, wind, reaction rates	Time averaged over replacement time, steady state	Unknown	Budd Inlet
Steady State 3-Dimensional Diffusion Model (Yearsley 1973)	Mass balance	BOD, DO and sulfite waste liquor concentration	Port Gardner	3-dimensional	Elements are 10 m thick through water water column	900 m^2 x 10 m	Tidal dispersion, sources, sinks	Steady state	Yes IBM 370	Port Gardner
Ecologic Modeling (Water Resources Engineers 1975) Several models combined	Partial differential equations, finite element	Nutrients, phyto, zooplankton, BOD, DO, benthic, fish	Puget Sound	1-dimensional, 2-dimensional, 3-dimensional parts	3 layer	5 km	Tide, gradient, discharge	Steady state or dynamic	Yes	Port Orchard, Dyes Inlet, Sinclair Inlet, Puget Sound, San Francisco Bay
Metro Mass Transport Model (In preparation)	Mass balance analytical model	Lateral and vertical transport of material, accumulation	Puget Sound Central Basin	1-dimensional longitudinal	2 layer	Variable but large	Tidal flows, discharge, gradient	Annual wet/dry	Yes	Puget Sound Central Basin
Puget Sound Circulation Model (Cokelet In preparation)	Harmonic decomposition, finite difference	Tidal heights and currents	Puget Sound Central Basin	2-dimensional horizontal	No	Variable - coarse 1 km fine 0.5 km	Tide	N/A	In future - Cyber 170/150	Puget Sound Central Basin
Nutrient Distribution Model (Winter and Pearson 1975)	Conservation of mass equations	Nutrient distributions, longitudinal velocity, tidal height, density	Puget Sound Central Basin	1-dimensional longitudinal	2 layer	N/A	Discharge, turbulent mixing, vertical convection	Steady state	Unknown	Puget Sound Central Basin
Barotropic Mixed Tides (Crean 1978)	Finite difference	Velocity	Strait of Juan de Fuca and Strait of Georgia	2-dimensional horizontal	No	2 km	Tide	23 sec	Yes	Strait of Juan de Fuca, Strait of Georgia
Tidal Currents in Strait of Georgia/Juan de Fuca (Crean In preparation)	Finite difference	Tidal height, velocity	North Sea	2-dimensional horizontal	Yes - 7 layers	4 km	Tide	45 sec	Yes - in future	Planned test area - Puget Sound
Modeling of Tides in East Passage (Jamart In preparation)	Finite element, harmonic decomposition	Free surface elevation, velocity	East Passage	2-dimensional horizontal	No	Variable	Tide, wind	N/A	Yes - in future	Planned test area - East Passage

Figure 5-1. Modeled Regions of Puget Sound, the Strait of Juan de Fuca, and the Strait of Georgia.

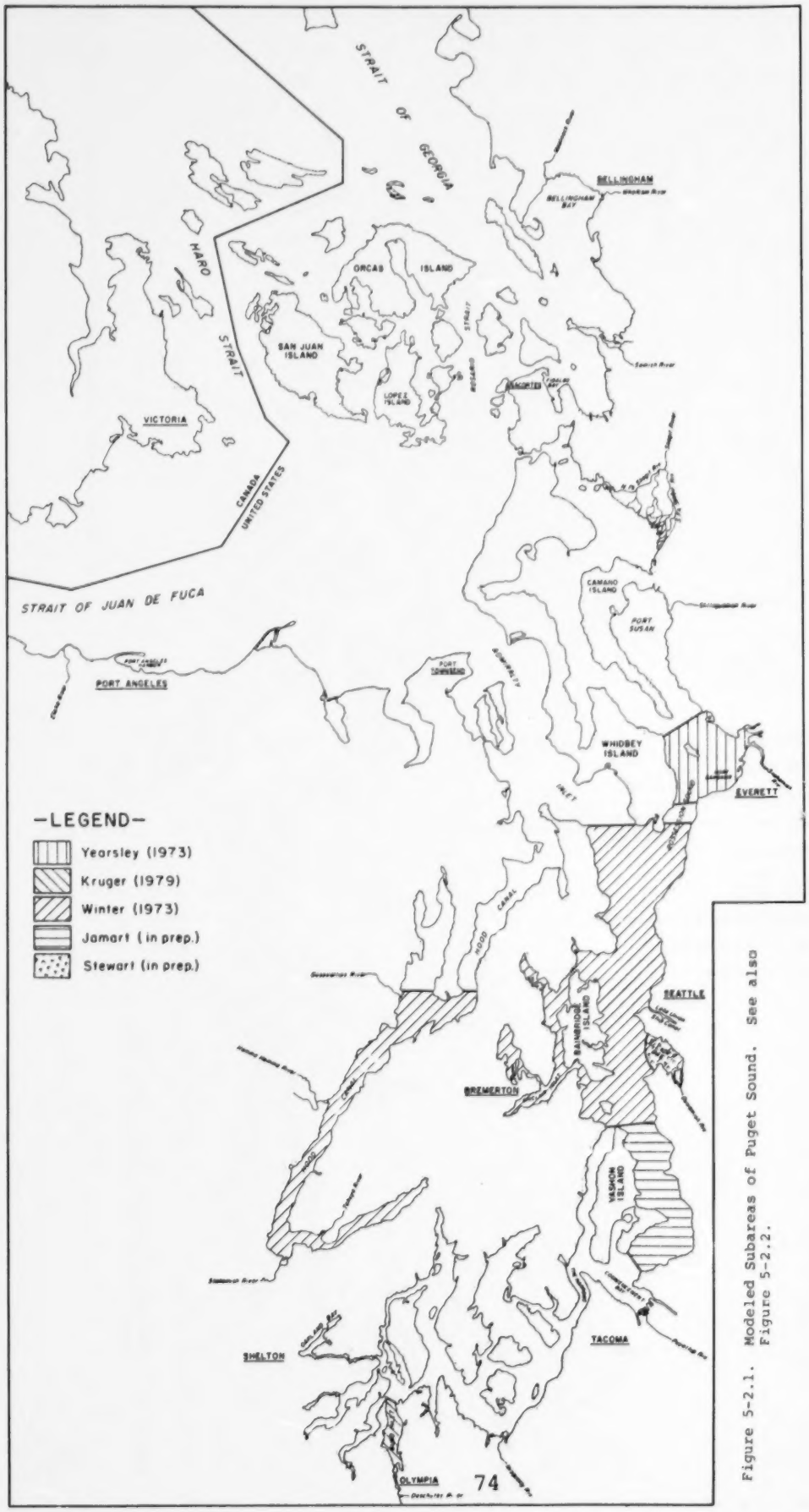

Figure 5-2.1. Modeled Subareas of Puget Sound. See also Figure 5-2.2.

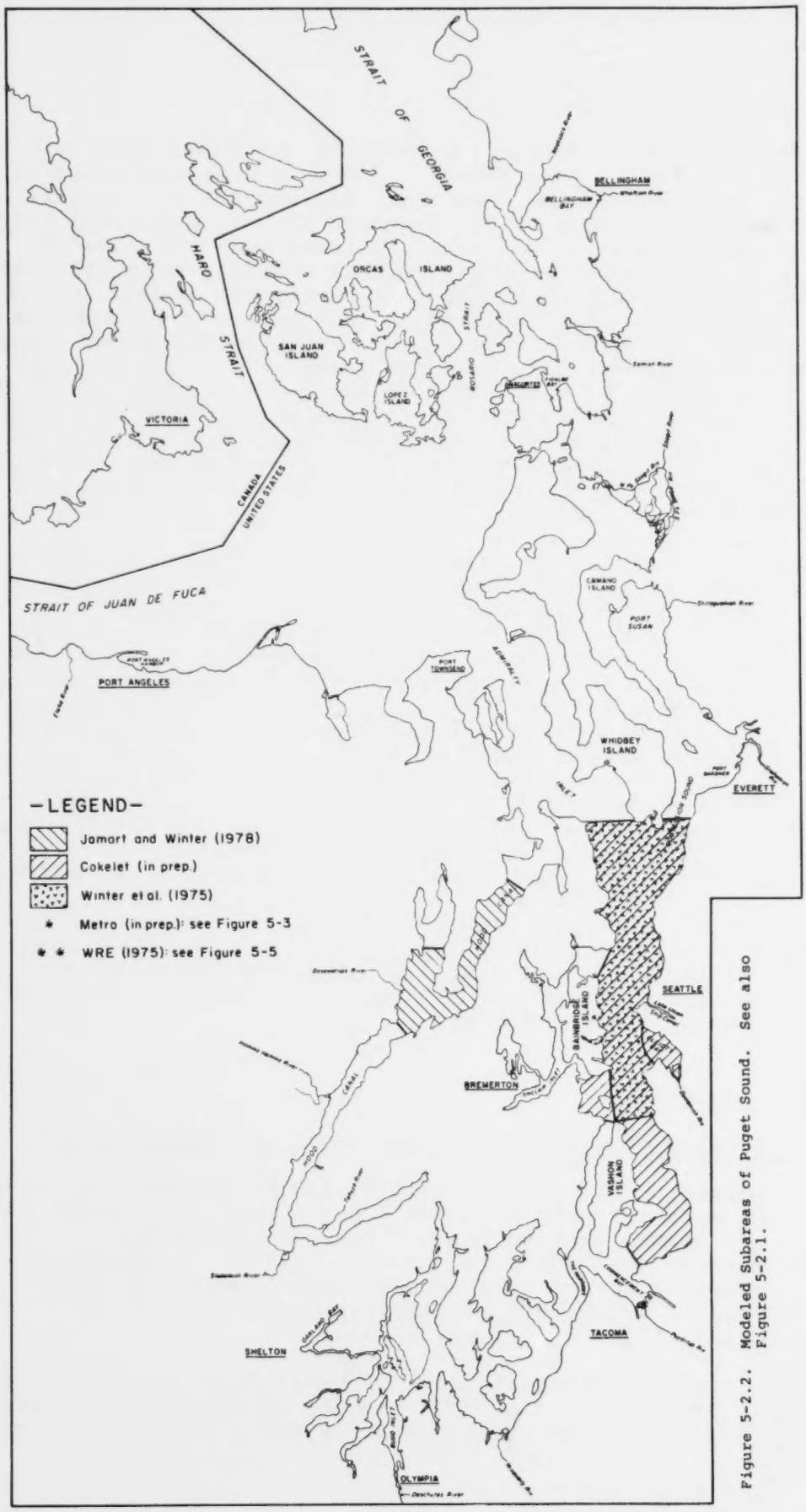

Figure 5-2.2. Modeled Subareas of Puget Sound. See also Figure 5-2.1.

Nearfield Plume Models

Nearfield plume models are briefly described here but not evaluated further in this report. Plume models are designed to describe the short-term behavior of buoyant or negatively buoyant waste discharges. For buoyant plumes, nearfield models describe the degree of dilution achieved and the size of the plume as it rises to a level of neutral buoyancy or to the water surface. Several different types of nearfield models are currently employed by EPA (several of which have been applied to Puget Sound). These models are very useful in computing initial dilution, height of rise, and the size of the plume (zone of initial dilution) at the level of neutral buoyancy or at the surface. As the name implies, nearfield models describe a waste field in the immediate vicinity of the discharge and only up to completion of initial dilution. A circulation and dispersion model is required to describe how wastes subsequently will be dispersed in Puget Sound.

Nearfield models, by themselves, are not appropriate as an overall waste management tool for Puget Sound because they cannot simulate the transport and fate of pollutants after completion of initial dilution. Nevertheless, the concept of initial dilution and the concentrations of pollutants after initial dilution are important from a waste management perspective. The circulation and dispersion (or farfield) model should be designed to be somewhat compatible with a nearfield model. The grid element of the farfield model to which the waste source enters should be approximately the same size as the zone of initial dilution computed by a nearfield model. In this way, the concentration of pollutants computed for the first element of the farfield model will be roughly similar to pollutant concentrations after initial dilution computed by a nearfield model. This technique for selecting the grid size for the farfield model node into which a waste discharges is not a substitute for nearfield plume modeling. It does provide, however, a means of realistically computing with the farfield model the highest concentration of a pollutant to be expected in the vicinity of a waste source.

Transport Models

University of Washington, Department of Oceanography.

- Barnes, C. A., J. H. Lincoln, and M. Rattray, Jr. 1957. An oceanographic model of Puget Sound. In: Proc. of the Eighth Pacific Science Congress 3:686-704.
- Rattray, M., and J. H. Lincoln. 1955. Operating characteristics of an oceanographic model of Puget Sound. Transactions, American Geophysical Union 36:251-261.

OBJECTIVE. A physical model of Puget Sound was constructed with funds provided by the Office of Naval Research to investigate the tidal currents in all of Puget Sound south of Admiralty

Inlet, including the Whidbey Basin. Prior to construction, a detailed theoretical study was undertaken to examine suitable model scales.

DESCRIPTION. The model was constructed at the University of Washington. The horizontal scale is 1:40,000 and the vertical scale is 1:1,152; all other scales were derived from these two by dimensional relationships.

FORMULATION. Tidal action is the principal driving force on the dynamic oceanographic processes occurring in Puget Sound. In the physical model, tides are generated by displacement of water by a plunger in a headbox. A tide computer of the Kelvin type controls the vertical movement of the plunger. The computer provides summation of six major tidal constituents to produce a tide within ±1 foot of the predicted prototype tide. Freshwater inflow is provided at the discharge sites of 11 principal rivers in Puget Sound. A separate tank simulates the ocean as a saltwater source and the ocean salinity is automatically adjusted to within 1 percent to compensate for dilution by river discharge.

STATUS. The model gives good representation of prototype circulation, current patterns, and velocities as determined by visual observations. The density structure in each of the four main sections of Puget Sound may be reasonably reproduced in the model.

ADEQUACY. No physical model having such a great degree of distortion can exactly reproduce the behavior of the prototype. This is especially a problem when examining local water quality and circulation processes in such important areas as Commencement Bay and Elliott Bay. Surface tension limits water movement in shallow and shoreline areas, rendering model predictions unreliable in these portions of the Sound. Since viscosity cannot be scaled in the model, this factor may impede flow through small channels and reduce the small-scale turbulence at these sections.

TRANSFERABILITY. The physical model is available at the University of Washington and a duplicate model was constructed for the Pacific Science Center, both located in Seattle. Data required to accurately portray characteristics of Puget Sound include the rate of flow of the 11 principal rivers, proper tide selection, and the density structure of the four main sections. Many of these data have been collected by various agencies and are available for use.

APPLICABILITY. The physical model can be used for insight into general basin-wide circulation and flow. Access to the model is limited an dit is not capable of predicting concentrations for many of the water quality variables that are of interest to EPA.

Farmer and Rattray (University of Washington, Department of Oceanography

- Farmer, H.G., and M. Rattray, Jr. 1962. A model study of steady-state salinity distribution in Puget Sound. Dept. of Oceanography Technical Rept. No. 85, University of Washington, Seattle, WA.

OBJECTIVE. The previously described physical model was employed to determine and model the steady-state salinity distribution of Puget Sound. The salinity within Puget Sound was observed to be strongly affected by the characteristics of the Admiralty Inlet tidal flow.

DESCRIPTION. The relative response of the different divisions of the Puget Sound system to changes in tide and runoff can be determined by the salinity distribution observed in the model. The model was operated at three conditions of freshwater runoff (low monthly, annual, and high monthly) and five values of tidal range. Salinity profiles were taken at seven stations throughout Puget Sound: off Bush Point, Camano Head, Hazel Point, Point Jefferson, Pully Point, Spring Beach, and Gordon Point.

FORMULATION. From the results of previous experiments it was discovered that the salinity distribution throughout the model varied little with moderate changes in the salinity scale. A salinity scale of 1:2 was selected for this study. Salinity dependence at a specific station is a function of tidal height, channel depth, river discharge, tidal flow, and Froude number. The vertical salinity profile was determined at each station by titration of small water samples taken at several depths. The parameters that were varied in the model experiments are the river discharge, the tidal height, and the tidal period.

STATUS. Previous studies have indicated that the density structure in the model may successfully reproduce that of the prototype. No actual field verification of the results was performed in this study although circulation patterns agreed well with other field studies.

ADEQUACY. The results of this study provide insight to the overall density structure and general circulation patterns of the main sections of Puget Sound. Use of the physical model introduces error by neglecting the effects of wind and viscosity on circulation and transport processes. This model provides basic information on density structure that could be utilized by other models or in future model development.

TRANSFERABILITY. The physical model is available at the University of Washington, Department of Oceanography.

APPLICABILITY. Experiments with the physical model may provide insight into general circulation modes, density distri-

butions, and flow, but the model cannot provide predictions for the biological and chemical constituents of interest to the EPA.

Friebertshauser and Duxbury (University of Washington Department of Oceanography).

- o Friebertshauser, M. A., and A. C. Duxbury. 1972. A water budget study of Puget Sound and its subregions. Limnology and Oceanography 17(2):237-247.

OBJECTIVE. The objective of this study was to determine the mean fluxes of water into and out of the subregions of Puget Sound and the change in freshwater content by month and by year for the areas.

DESCRIPTION. A water budget study was conducted to quantitatively describe the net circulation in Puget Sound. The budget approach is simply a mass balance equation assuming that the volume of water and total salt content in an estuary, averaged over a given time period, are constant.

FORMULATION. The water budget analysis allows for calculations of fluxes of water and salt and flushing times. Three budgets are considered: total water, fresh water, and sea water. Assuming that mixing does not occur between inflow and outflow, and that inflow water is completely mixed within the basin, the flushing time is expressed as the volume of water in the basin divided by the average rate of outflow.

STATUS. The water budget equations were applied to four subregions of Puget Sound: Whidbey Basin, Hood Canal, Central Basin, and Southern Basin (Figure 5-1). Data required to run the model include: the freshwater contribution composed of river discharge and direct precipitation minus direct evaporation; changes in water volume as indicated by tide level; and, the average salinities of inflowing and outflowing water.

ADEQUACY. The water budget model can indicate patterns of net circulation in descriptive terms. Methods for accurately determining variables in the equations are lacking. Adequate data are not available for several variables including evaporation rates on a monthly basis and ungaged river flow. The budget analysis assumes that the change in sea level at Seattle is representative of the entire Sound and that the surface area does not change with sea level. Also, inflowing water is assumed to be completely mixed within the basin and the inflowing and outflowing water does not mix. The approach of this model is universal, but accuracy of the calculated fluxes will depend on the accuracy of the estimated variables and data availability.

TRANSFERABILITY. Data availability appears to be the important factor in obtaining reasonable results with this model. Data sources for the Puget Sound area include: Water

Resources Data for Washington, Climatological Data for Washington, and the National Environmental Satellite, Data, and Information Service.

APPLICABILITY. The model is of use in determining net flows through different regions of Puget Sound, considered on a monthly or yearly basis. However, much more detailed information is required by the EPA to adequately predict the effects of discharges on a local, short-term basis. Circulation processes within each basin need to be described. Formulations in this model enable the calculation of overall residence time and net flow but not detailed circulation patterns.

Winter (University of Washington Department of Oceanography).

- Winter, D. F. 1973. A similarity solution for steady-state gravitational circulation in fjords. Estuarine and Coastal Marine Science 1:387-400.

OBJECTIVE. Analysis of steady-state gravitational circulation in the near surface zone is the topic of this study. This is the dominant circulation mode in fjords that receive substantial freshwater input.

DESCRIPTION. Circulation in the upper layers of stratified fjords is represented as a steady-state process by time averaging the equations of motion over a tidal cycle.

FORMULATION. The governing equations are written in terms of nondimensional variables. Approximate analytic representations are calculated for the velocity and density distribution in areas where conditions allow for a similarity analysis. The basic formulation consists of three partial differential equations in the form of Navier-Stokes equations. A similarity solution is used to derive a single nonlinear differential equation that is solved by a power series approximation. Assumptions made in the formulation include: neglect of Coriolis effects; limitation to narrow, straight segments where the velocity and pressure differences across the channel are negligible; and application to fjords with freshwater runoff inputs that produce a mean surface current directed seaward. A wind factor is not incorporated into the model, and the influence of the tide is indirect. The changes in runoff quantities and wind stress are ignored and the solution assumes an infinite channel depth such that bottom friction does not play an important role. All equations are averaged over the tidal cycle to give the long-term average circulation.

STATUS. The model has been applied to the Hood Canal and the Central Basin (Figure 5-2) and to Knight Inlet in British Columbia. Input to the model includes cumulative runoff, variable channel width, and eddy diffusion coefficients. The

vertical eddy diffusion coefficient was calibrated from field measurements.

ADEQUACY. The predicted salinity distributions follow the general pattern of the measured profiles. Variation of input parameter values can increase the agreement between predicted and measured values. The model gives the principal features of the flow and salinity distribution on a steady-state basis for long narrow fjord-like water bodies where gravitational circulation is the primary circulation mode. Description and presentation of application results are brief, and it is evident that the model cannot generate detailed information about circulation and density distributions as they change with time. The model lacks general applicability to a variety of locations and conditions due to the limitations and assumptions incorporated into the basic equations.

TRANSFERABILITY. Similarity solutions reduce to a 1-dimensional problem on a computer. These solutions could be easily handled on machines with limited computing ability.

APPLICABILITY. To satisfy EPA's objectives, a dynamic model formulation may be required. The formulation presented here is steady-state and is also limited to application in narrow, straight channels.

Pease (Pacific Marine Environmental Laboratory).

- Pease, C. H. 1980. An empirical model for tidal currents in Puget Sound, Strait of Juan de Fuca and southern Strait of Georgia. EPA-600/7-80-185, Pacific Marine Environmental Laboratory, Seattle, WA.

OBJECTIVE. This empirical model was developed to provide tidal current input for oil spill trajectory modeling and surface drifter analysis for the Puget Sound MESA project.

DESCRIPTION. The model employs National Ocean Survey (NOS) tidal constituents and current measurements for 157 stations in Puget Sound and interpolates between these measurements to obtain estimations of current speeds and directions throughout the Sound.

FORMULATION. A regional base grid of 1 km sections was defined for the study area. The grid has 223 segments on a side and is divided into 760 groups of sections having similar tidal velocity and direction, and interpolation coefficients. For each group, one to three current meter stations were subjectively assigned to represent currents in that group. Each assigned current meter received a weighted coefficient which reflected its relative importance to the group. Weighting coefficients ranged from 0.1 to 1.0, depending on several factors including location, cross-sectional area and streamline dependence. Tidal current speed throughout the basin is assumed

to be symmetric between ebb and flood, and the ebb and flood tide flow directions are assumed to be separated by 180°.

STATUS. Preliminary verification of the empirical model consisted of a detailed comparison of predicted current velocities with NOS Tidal Current Tables for 1978. This comparison showed that the model agreed with the NOS predictions with respect to phasing and the relative timing of the diurnal tide components, but the model velocity predictions were typically 20 percent lower than the NOS current velocities and agreement between the two varied throughout the study area. The model covered all of Puget Sound and the Straits as shown in Figure 5-1.

ADEQUACY. Several methods of interpolation are available; however, due to the complexity of the Puget Sound area, the method of applying a fixed relation to predetermined current stations was used to develop the formulation. The empirical model may be used to generate tidal current input with certain limitations. There are significant velocity scaling differences between the model and the NOS tide tables which are best handled on a case by case basis. Also, the flood values are reduced and the ebb values are enhanced in the NOS tide tables because the tables add an assumed mean velocity to the ebb current.

The model could be improved by reassigning the interpolation coefficients for the current stations based on a hydrodynamic model of tidal currents instead of by subjective decision, and by allowing ebb directions to be determined separately from flood such that asymmetric flows could be generated.

TRANSFERABILITY. The empirical model was constructed and computerized as a library containing functions and subroutines which are accessed directly by the user's model. The model was initially run on twin CDC 7600 computers. The FORTRAN source code and data used are on microfiche included in the listed reference. A user's guide and short description of all subroutines is also included. A card image tape that must be modified to direct access form is available from NOAA in Seattle.

APPLICABILITY. The model presents a method to expand a data base. EPA could not directly use this model but may utilize the formulation to estimate current velocity at points where data are unavailable. The model does not describe circulation processes. Average surface layer velocity only can be empirically determined.

Jamart and Winter (University of Washington Department of Oceanography).

- Jamart, B. M., and D. F. Winter. 1978. A new approach to the computation of tidal motions in estuaries. Pp. 226-281. In: J.C.J. Nihoul, ed., Hydrodynamics of

estuaries and fjords. Elsevier Scientific Publishing Company, Amsterdam.

OBJECTIVE. This paper describes a procedure for computing the periodic tidal motion in estuaries.

DESCRIPTION. The model consists of the equations for the conservation of mass and horizontal momentum. These time-dependent equations are vertically integrated to give 2-dimensional representations in the horizontal direction.

FORMULATION. The tidal motion in an estuary is periodic and therefore the dependent variables can be decomposed by a Fourier transformation. The advective and frictional components of the model are evaluated using an iterative procedure to avoid handling of the nonlinear terms by Fourier decomposition. The basic equations are rewritten as modal equations which are rephrased in terms of a variational principle. The final solution of the flow variables (free surface elevation and depth-averaged velocity) is obtained using the finite element method. The effects of convective acceleration, Coriolis acceleration, wind stress, and bottom friction are not addressed in the model. Assumptions inherent in the formulation include a linearized bottom friction term, a free surface elevation that varies linearly within subdivisions of the finite element grid, and vertical averaging of tidal velocities.

STATUS. A portion of Hood Canal (Figure 5-2) was used as the test region for the model. Model inputs are free surface boundary conditions and tidal frequency. Circulation and eddy patterns predicted by the model reproduce the physical hydraulic model data with respect to scale and location. Quantitative comparisons of these data were not conducted on these preliminary results due to simplifications in the equations for preliminary analysis.

ADEQUACY. The model has not been quantitatively verified but shows great potential as a tool for predicting tidal height and velocity. The model formulation deals more accurately with homogeneous estuaries where the estuarine circulation mode (stratified flow) is weak. A version of the same model has recently been applied to Knight Inlet in British Columbia, which exhibits a sill and fjord-type flow. Results of this application indicated that the model, although vertically averaged, can adequately simulate tidal propagation and depth-averaged velocities. The finite element grid must be sufficiently fine in regions of rapid change to satisfy the assumption that the free surface elevation varies linearly within each grid area. The mesh resolution should also be finer in questionable areas and areas of primary interest. A major advantage of this model is the treatment of time integration with respect to horizontal location. Unlike typical time-stepping models, the time variable is chosen independent of the other variables, resulting in a highly efficient and cost-effective computation.

TRANSFERABILITY. The model program for Hood Canal was run on a CDC 7600 computer with large core memory. The mass storage utilizes 125,000 words.

APPLICABILITY. The methodology presented is, in all practicality, limited to areas where stratified estuarine flows are weak or nonexistent. However, the model holds promise for two types of applications: a crude, depth-averaged model of the entire Puget Sound to provide approximate tidal flows on a regional basis; and refined applications in subregions of Puget Sound where vertical mixing is dominant over estuarine circulation.

Jamart (URS Engineers, Seattle, WA).

- Jamart, B. M. 1982. Report on the preliminary modeling of tides in East Passage, unpublished report prepared for Municipality of Metropolitan Seattle by URS Engineers, Seattle, WA.

OBJECTIVE. This model applies the formulation developed by Jamart and Winter (1978) to the East Passage of Puget Sound to compute the periodic tidal motion around the proposed Seahurst outfall area.

DESCRIPTION. Barotropic tidal motions are well described by conservation of mass and horizontal momentum equations which are vertically averaged and time dependent.

FORMULATION. The basic formulation is identical to that previously described in Jamart and Winter (1978). The selected study area is the East Passage of Puget Sound shown in Figure 5-2.

STATUS. The model is currently being developed by Dr. Bruno Jamart under contract to Metro. Preliminary calibration for the East Passage involves boundary condition specification and estimation of dispersion coefficient. Further data collection via a tide measurement program has been undertaken to better characterize tides in the East Passage.

Stewart (Pacific Marine Environmental Laboratory, NOAA).

- Stewart, R. J. 1982. Pollutant transport dynamics in estuaries. OMPA Annual Report 1982, National Oceanic and Atmospheric Administration (In preparation).

OBJECTIVE. The objective of this 3-year study is to develop theoretical and empirical techniques to better characterize the accumulation, resuspension, advection, and diffusion properties of the Duwamish River estuary.

DESCRIPTION. Models are currently being reviewed for possible application to this estuary. The model capabilities must include: ability to predict the movement of the salt wedge as a function of runoff and tide, and a method for estimating resuspension and exchange of sediments. NOAA is considering achieving these goals by collection, analysis, organization, and extrapolation of field data for input to a new or existing model.

FORMULATION. The process of major interest is the mass flux of suspended materials from the low salinity upper layer to the salt wedge. An explicit analytical model of the upper layer would be based on the assumptions of a well mixed upper layer of variable depth containing particles of varying size and density, residing on a quiescent lower layer of higher density. Particle density distributions are calculated from Coulter counter data by utilizing an explicit model of particle settling beneath a free surface in a homogeneous fluid. Another analytical model will predict the concentration of particles at depth, assuming constant diffusivity and spherical shape. A plume model is utilized to describe the potential contribution of the plume to pollutant transport in Elliott Bay.

STATUS. Several tests were conducted to examine the validity of the assumptions and basic formulations. The particle settling model, which employs a Bayesian inference method, was shown to be feasible, but the present numerical technique requires large, direct-access, mass storage files. Fluxes and rates of the model's transport processes in Elliott Bay are much larger and faster than in the Duwamish, therefore some length scales may be overestimated. Preliminary studies of the buoyant lens characteristics show a very large mass transport over short time scales on the order of a few hours. Future focus will be on the development of a quantitative model to locate deposition sites, which will require additional field data and experimentation.

TRANSFERABILITY. Only preliminary formulations, assumptions, and studies have been prepared at the present time.

APPLICABILITY. Sediment processes are of major interest to EPA. This model is in the development stage. Application of the developed empirical model to other sites may be limited due to the apparent dependency on field observations of the sediment transport behavior in the Duwamish River.

Seattle Metro Transport Model.

- Seattle Metro 1983. Toxicant Pretreatment Planning Study report, In prep. (Pavlou, pers. comm.).

OBJECTIVE. Metro is currently developing a model to predict lateral and vertical transport of materials and pollutants, forecast pollutant concentrations, and determine

pollutant flushing rates and residence-times throughout the Central Basin.

DESCRIPTION. A box-type analytical model of the volume transport and eddy fluxes is being developed. The main basin of Puget Sound was divided into 11 sections (Figure 5-3) with a hydrographic station centered in each section.

FORMULATION. The model employs a layering technique; each section consists of an upper layer and a lower layer. The interface between these layers was selected as 50 m, which corresponds to the depth of no net flow. The basic assumptions of the model are conservation of mass and balance of salt flux. The upstream salt flux is considered to be zero, that is, the salt balance is achieved by advection. A schematic of the computational configuration is shown in Figure 5-4. The vertical volume transport (Q_{vi}) from upper to lower layer can be calculated by applying mass and salt balance equations to the lower layer.

Settling rate is incorporated into the model as a constant value for each element. The rate is estimated from ^{210}Pb decay analysis of sediment cores taken from Puget Sound.

STATUS. The model is currently under development and there is no documentation available at present. The model will be calibrated at low and high flow conditions.

ADEQUACY. The existing spatial grid is too large for the detailed predictions necessary in some parts of Puget Sound. Finer grid resolution is necessary in the vicinity of waste discharges. Certain areas of specific interest (e.g., Elliott Bay) serve only as input to the model. Resuspension is not specifically addressed, but is incorporated into the total sedimentation rates determined by dating sediment cores. The calculated settling rate from the lead distributions should represent the sedimentation from natural sources, but may not adequately represent the increased sedimentation due to increased waste inputs in the future. Suspended particulate loading and sedimentation rates are linked in the model and allow projections based on increased or decreased mass loading. The model formulation is basically 1-dimensional to the extent that lateral gradients, which may be important in the Central Basin, are neglected.

TRANSFERABILITY. Information on computer requirements, programs, and data accessibility is not available at this time.

APPLICABILITY. Sedimentation processes in Puget Sound are of primary concern to EPA but the model in its current state would not be appropriate to obtain the necessary detailed information required for water quality management decisions. Calibration, verification, and finer resolution are needed for the model to be useful.

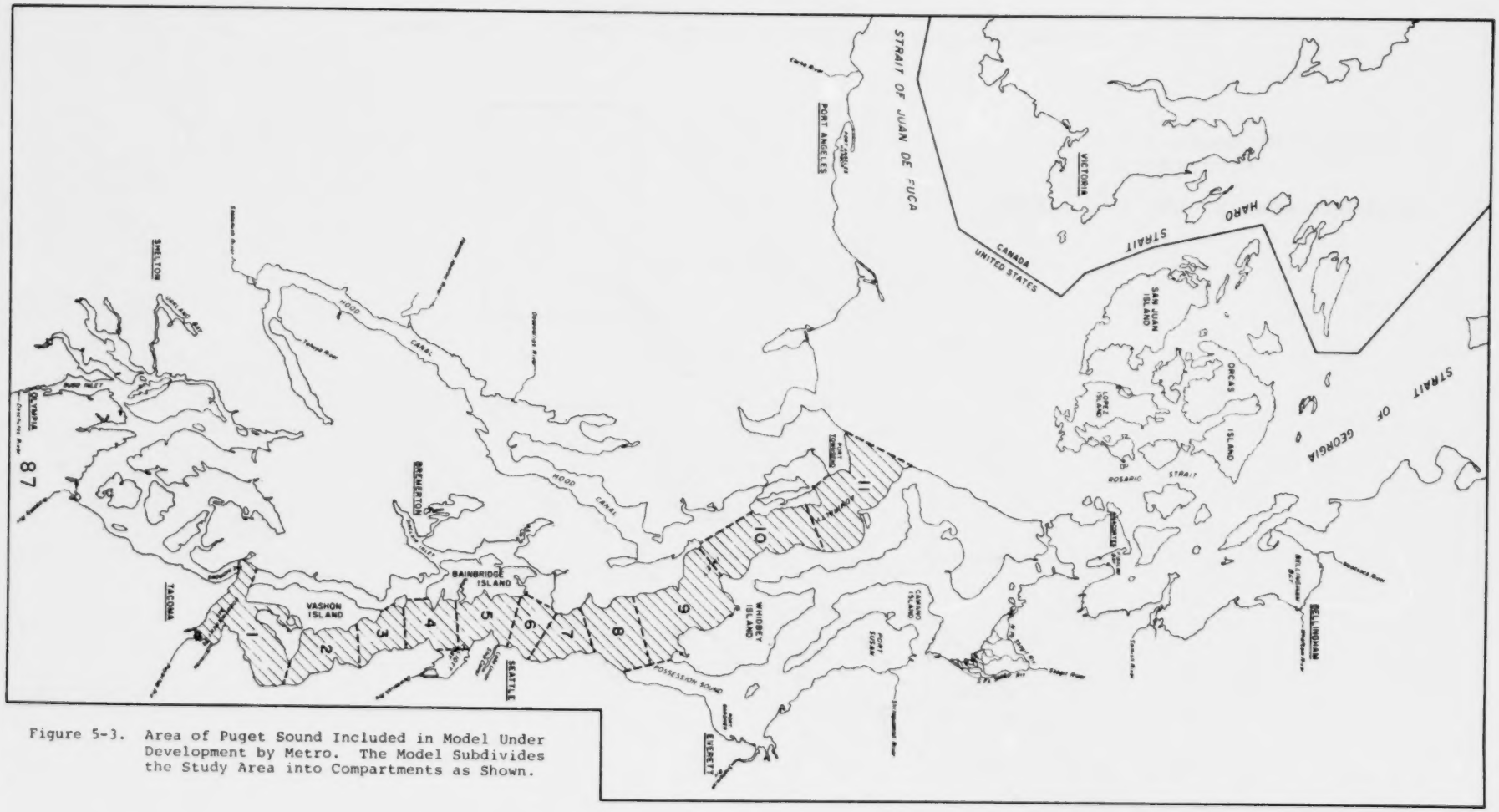

Figure 5-3. Area of Puget Sound Included in Model Under Development by Metro. The Model Subdivides the Study Area into Compartments as Shown.

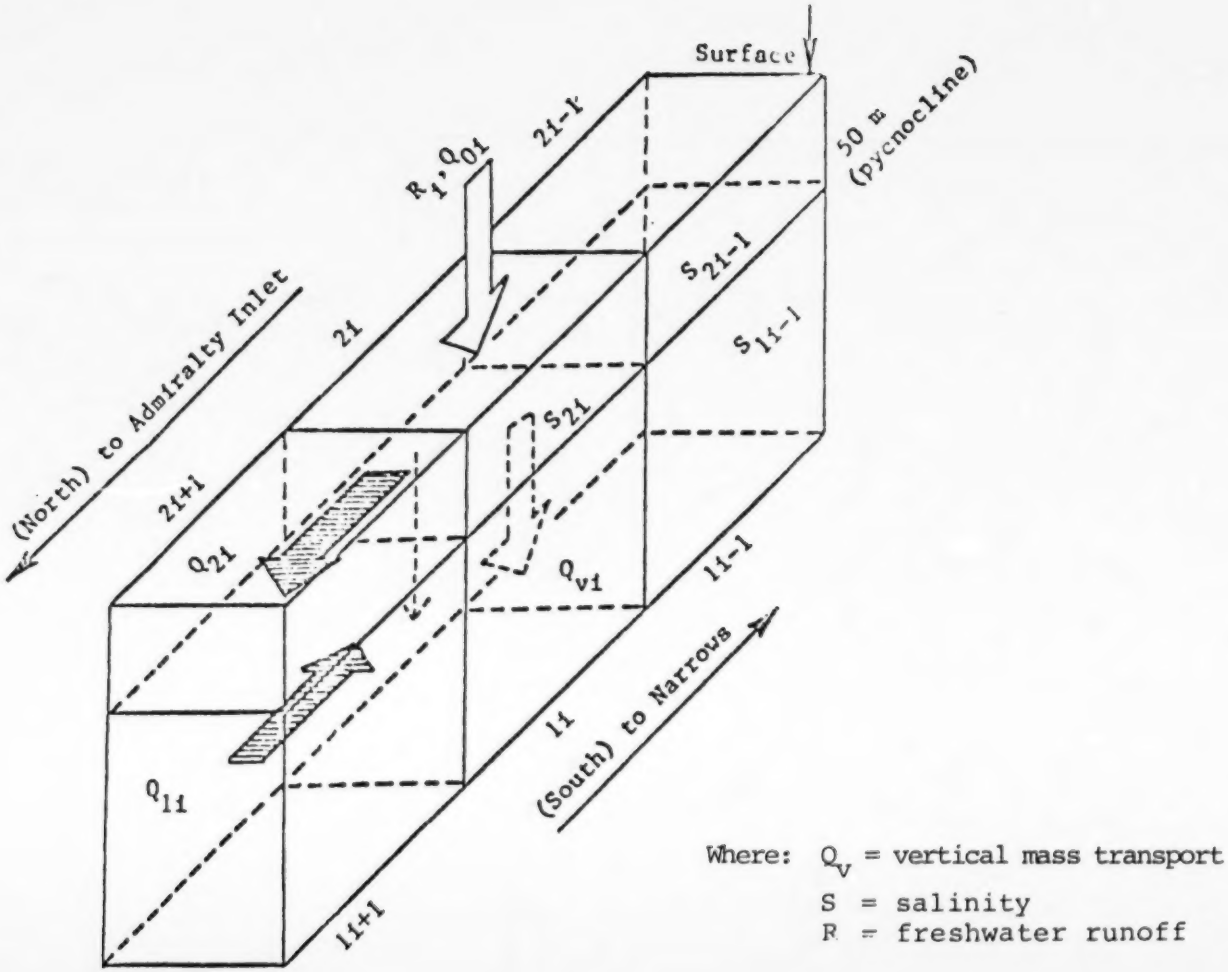

Figure 5-4. Schematic Diagram of the Compartmental Configuration for the Box-Model Calculation (Metro 1983).

Cokelet (Pacific Marine Environmental Laboratory, NOAA).

- o Cokelet, E. 1982. (pers. comm.) Long range effects research program. Office of Marine Pollution Assessment, 202 Program. Description of Circulation Model (in preparation).

OBJECTIVE. The model will predict tidal circulatory processes for use in determining the role of particulates in estuarine and coastal pollutant transport.

DESCRIPTION. Several modes of circulation are present in water bodies such as Puget Sound including estuarine, wind driven, and tidal modes. This model attempts to predict the circulation caused by tidal phenomena. The model deals with the mean circulation (monthly or yearly basis) and predicts tidal height and currents.

FORMULATION. The formulation consists of vertically integrated, 2-dimensional equations of motion describing baroclinic tidal processes in a homogeneous fluid. These equations are Fourier decomposed in time and solved by a finite element formulation. The finite element grid consists of triangular sections of 1 km on a side for the coarse grid and approximately 0.5 km lengths for the fine grid. The fine grid will be utilized for problem areas, areas of specific interest, and areas with complex circulation patterns. This formulation is similar to that presented by Jamart and Winter (1978).

STATUS. The model is currently under development and is scheduled to be operational by the end of 1983. Input data include tidal heights or currents at the boundaries and selection of the finite element grid. The future test area for verification of the model will be the main basin of Puget Sound (Figure 5-2). A field cruise was conducted in March 1983 to collect data for use in verification.

ADEQUACY. For accurate representation by the model, the selected area must display little or no stratification and require no resolution in the vertical direction. Only the mean circulation is modeled, so variation of variables on a small time scale is not considered. This formulation would have limited use for general applicability.

TRANSFERABILITY. The program source code will be written in FORTRAN IV and will be machine independent. The computer selected for final simulation of the model will be a Cyber 170/150 and computer requirements include approximately 200K storage capacity. The coastal physics group at NOAA has a data archive system which is available for use on all historical measurements. If the developed program source code may be used without significant modification, the model can be adapted and computerized in a few months.

APPLICABILITY. The model would have limited applicability to broad-scale water quality management studies because of limitations in handling stratified conditions, and in resolving significant vertical variation of water quality variables. However, this model, once developed and verified, may be useful in areas of Puget Sound where vertical homogeneity is present, e.g., Liberty Bay and Dyes Inlet.

Cokelet and Stewart (Pacific Marine Environmental Laboratory, NOAA)

- Cokelet, E. and R. Stewart. 1983. A simple model to estimate the exchange of water in fjords with sills. For: Long Range Effects Program, OMPA. In preparation (Cokelet, pers. comm.).

OBJECTIVE. Research is underway on the development of a model to describe the flow and exchange of water through Puget Sound. Once the water pathways have been determined, this knowledge may be used to predict the steady-state distribution of soluble, conservative tracers.

DESCRIPTION. This model quantifies the efflux and reflux characteristics of the Central and Southern Basins in Puget Sound. The study area is divided into advective reaches and mixing zones. Within the mixing zones, water may be vertically exchanged or transported out of a basin. If a majority of the flow is refluxed into an advective reach, pollutant accumulation results.

FORMULATION. The model formulation is based on the modification of a box model. Modifications include the assumption of negligible vertical entrainment between the upper and lower layers in advective reaches and division of the study area into two classes of reaches: advective reaches and mixing zones. Mass balance equations are written for each reach using salt flux and flow and are solved simultaneously.

The study area under consideration includes the Southern and Central Basins of Puget Sound. The Whidbey and Hood Canal basins are treated as inputs to the Central Basin. The Central Basin contains three advective reaches and the Southern Basin is made up of two. Preliminary selection of mixing zones includes the area from Alki Point to West Point, Admiralty Inlet, Tacoma Narrows, and a terminal mixing zone in the Southern Basin. The size of the subdivisions range from 10-20 km long and contain an upper and lower layer.

STATUS. The model is currently under development. Preliminary calibration of the mass fluxes for the Central Basin has been conducted, and results indicate that the delineation between mixing zones and advective reaches should be modified. Input data required by the model to simulate a simple estuary include salinity, river inflow, and precipitation

for each reach. Additional conservative tracers (other than salinity) are needed to model multiple branch estuaries.

ADEQUACY. Results of the preliminary application to Puget Sound show good agreement with previous work on calculation of reflux coefficients for the Central Basin (Ebbesmeyer and Barnes 1980). The formulation is very sensitive to the salinity values input into the model and more work is needed to revise available data.

TRANSFERABILITY. The program is a very simple matrix representation of sets of simultaneous equations that may be run on any system with minimal time and effort. The FORTRAN code will be readily available after model verification procedures have been completed and model results have been published.

APPLICABILITY. This model is only capable of describing the gross movement of water through the study area. This information will allow estimates of reflux and efflux coefficients at primary mixing zones throughout the Central and Southern Basins. Water quality variables, suspended solids transport, and solids accumulation processes are not considered and cannot be added without significant modification. The predictive capability is limited to steady-state concentrations of conservative, soluble substances over extensive areas. This model could be used in conjunction with other models to aid in understanding the complex processes occurring in mixing zones in Puget Sound.

Crean (Institute of Ocean Sciences, British Columbia, Canada).

- Crean, P. B. 1978. A numerical model of barotropic mixed tides between Vancouver Island and the mainland and its relation to studies of the estuarine circulation. Pp. 283-313 in: Hydrodynamics of estuaries and fjords. Elsevier Scientific Publishing Company, Amsterdam.

OBJECTIVE. The objective of this model is to obtain a quantitative description of the physical processes that determine the flow through the Strait of Juan de Fuca and Strait of Georgia. The model is designed for use as input to ecological models relating to the major fisheries of the area.

DESCRIPTION. The model predicts velocity and tidal height for points on a finite difference grid for the Strait of Juan de Fuca and the Strait of Georgia.

FORMULATION. The system is represented by a set of vertically integrated equations for continuity and momentum applicable to tidal motions in a flat, rotating sea. The equations are solved by stepping through time using a finite difference

approximation. The formulation includes the Coriolis effect and utilizes a uniformly applied coefficient of friction. The derivation of the equation assumes that velocity is independent of depth.

STATUS. The model was verified using a test area encompassing the Strait of Juan de Fuca, the San Juan Islands and part of the Strait of Georgia, extending northward of the area shown in Figure 5-1. Agreement was obtained between computed and observed tidal harmonic constants. One-dimensional models have been utilized to represent areas of flow into the test region for simplification of the boundary conditions. Input data include boundary condition specifications such as tidal height or velocity, and river inflows.

ADEQUACY. The model was able to predict tidal velocities accurately in the Strait of Georgia and the outer portion of the Strait of Juan de Fuca. Difficulties were encountered when simulating the straits and passages in the San Juan Islands. More detailed adjustments of the friction coefficient are advised for this region. An obvious limitation of the formulation is the apparent lack of vertical resolution of velocity.

TRANSFERABILITY. Necessary data for calibration procedures and comparison to computed values are available from the Canadian Hydrographic Service, which has gathered extensive water elevation and current data. Availability of the numerical model is not known.

APPLICABILITY. This model is a standard, explicit, 2-dimensional in the horizontal, finite difference circulation model. There are numerous models of this type available for use in Puget Sound if desired. This type of model is costly to operate on a large scale, however, and is limited in application to areas exhibiting vertically well mixed conditions.

Crean (Institute of Ocean Sciences, British Columbia, Canada).

- Crean, P. 1982. (pers. comm.). Description of 2-dimensional, layered model for prediction of currents in Straits of Georgia-Juan de Fuca (in preparation).

OBJECTIVE. The objective of this model is to accurately quantify and predict the physical processes that affect the flow through the Strait of Juan de Fuca and Strait of Georgia region. Tidal currents are modeled for use in other ecological models. This model was originally developed for the North Sea by the University of Hamburg, Institute of Oceanography.

DESCRIPTION. The formulation models the tidal height and velocity for points throughout a finite difference grid. The model is 2-dimensional in the horizontal plane and layers the

water column into seven sections, approximately 6, 9, 18, 27, 46, 76, and 125 meters deep.

FORMULATION. The system is represented by a set of equations for continuity and momentum for the seven layers. The equations are solved by stepping through time using a finite difference approximation and a time step of 45 seconds. The effects of Coriolis acceleration and bottom friction are included in the equations. The finite difference grid size was 4 kilometers.

STATUS. The formulation is under development and publication of results is expected in the fall of 1983. The Straits of Georgia and Juan de Fuca area have been selected as the future calibration site. Input data include boundary condition specifications such as tidal height or velocity and river inflows.

ADEQUACY. Verification and calibration efforts have not been completed so the accuracy of the model is unknown at this time. Important factors in the model accuracy will be the characterization of mixing and net flux between the layers and layer interface boundary conditions.

APPLICABILITY. Since the model has not been applied to Puget Sound and accuracy of the formulation is unknown, applicability is also presently unknown.

Water Quality Models

Winter, Banse, and Anderson (University of Washington Department of Oceanography).

- Winter, D. F., K. Banse, and G. C. Anderson. 1975. The dynamics of phytoplankton blooms in Puget Sound, a fjord in the northwestern United States. Marine Biology 29:139-179.

OBJECTIVE. The objective of this study was to quantitatively describe the relationship between climatic and hydrodynamic conditions and primary production in fjords.

DESCRIPTION. In this study phytoplankton standing stock was represented by chlorophyll a concentration. The model predicts the change in chlorophyll a concentration with time due to the effects of transport by turbulent mixing and advection, photosynthesis and respiration, grazing, and sinking. The equations were averaged over the channel width and over the tidal cycle.

FORMULATION. The model considered only the surface layer to a depth of 30 m. A laterally averaged partial differential equation for chlorophyll a representing the system and boundary conditions was estimated using field observations. The change

of chlorophyll a with respect to the longitudinal dimension was found to be negligible and the original 3-dimensional problem was transformed to two dimensions. To compensate for changes in cumulative runoff rate and intensity of turbulent mixing, the salinity distribution and nontidal flow field were calculated daily from field data.

STATUS. The formulation was applied to the Central Basin (Figure 5-2). Several numerical experiments were conducted on the biological submodels to determine the accuracy of parameters, many of which were selected from the literature. Results of these experiments showed that the predictions were sensitive to the values for grazing rates, maximum photosynthetic rate, sinking rate, and the method of incorporating self-shading into the model. Limitations of the present equations occur in systems where there is sustained low nutrient availability and where intense algal blooms lower the dissolved oxygen concentrations for extended periods. The sinking rate cannot be easily measured in the field and the values for specific photosynthetic rate and light saturation should be obtained directly for the particular algal community. A single grazing function is used that is independent of size or species of herbivores. Several parameters are assumed constant with depth including carbon to chlorophyll a ratio and sinking rates. General data requirements include net specific production rate, nutrient limitation factors, light intensity and respiration, grazing, and sinking rates. Further research is advised to aid in the description of respiration processes, light extinction coefficients, and grazing effects.

ADEQUACY. The model predictions and subsequent numerical experiments demonstrate a close interaction between primary productivity and circulation, climatic conditions, and physical and chemical properties of Puget Sound. Primary productivity in the Central Basin is affected by several hydrodynamic factors such as upwelling and turbulence. Results of the model show that the predictions reproduce the general features of observed primary productivity, but more research is needed to better define certain parameters.

TRANSFERABILITY. No solution procedure is discussed in the paper. The formulation requires fine calibration and extensive field observations.

APPLICABILITY. Phytoplankton growth is an important variable in water quality evaluation. The model uses simplified formulations to simulate the circulation processes which are of major concern to EPA. Much of the input to the model was estimated from field observations which tend to be time, labor, and cost intensive. The model is narrow in scope and would have limited applicability to EPA's water quality management program.

Stevens, Thompson, and Runyan, Inc. (Seattle, WA).

- o Stevens, Thompson, and Runyan, Inc. 1975. Puget Sound regional assessment study. Prepared for National Commission on Water Quality. Vol. II, pp. 189-214.

OBJECTIVE. A model was devised to simulate natural nutrient distributions and to predict changes caused by external loadings.

DESCRIPTION. Water movement is characterized by a two-zone description, a surface layer and a deeper zone. Each zone is characterized by an average horizontal velocity, mass density, and depth. Transport between the zones takes place by vertical convection and turbulent mixing.

FORMULATION. The model consists of equations of conservation of volume, mass, and horizontal momentum for each zone, which results in six coupled nonlinear differential equations. The equations are averaged over the tidal cycle and are solved by the Runge-Kutta method. The nutrient loading from external sources was expressed as accumulation from several areas to be released at specified locations. Nutrients were assumed to be transported within the Sound by the same hydrodynamic processes that determine the salinity distribution. Information such as horizontal velocity and convective and turbulent exchange were obtained from the physical model by unspecified methods. The concentrations in the lower zone at Admiralty Inlet were assumed to be unaffected by the Sound. Equations for the nutrients in the two zones were derived using conservation principles and a steady-state solution was obtained.

STATUS. Model calibration was performed for the main basin of Puget Sound (Figure 5-1). The circulation model yields hydrodynamic predictions that are utilized in the nutrient distribution estimates. Data required to utilize the model include cumulative freshwater runoff rate, vertical fluxes between zones, horizontal salinity gradients, vertical density gradients, net average horizontal current speeds, and external nutrient loadings.

ADEQUACY. Model results are reasonably consistent with oceanographic data, indicating that the gross features of Puget Sound have been adequately represented. The model predicts the steady-state nutrient distribution at several points throughout the main basin of Puget Sound. Assumptions inherent in the formulation include: accumulating runoff from several areas for release at various points in the basin; ignoring nutrient uptake by phytoplankton because it is a transitory, short-term effect; and disregarding tidally induced horizontal dispersion. The model formulation tends to underestimate the salinity increase seaward of the Admiralty Inlet sill. Predicted vertical profiles of the horizontal current velocity bear only a slight resemblance to observed tidally averaged currents, although few data are available for comparison. Most data have been acquired in areas where the current patterns are strongly influenced by

local bathymetry. Since nutrients are considered as conservative substances, settling of nutrients associated with particulate matter was not allowed.

TRANSFERABILITY. Computer requirements and program availability were not discussed.

APPLICABILITY. The model predicts steady-state nutrient distributions only and the formulation is basically 1-dimensional. Puget Sound is too complex to be represented by a 1-dimensional formulation. Greater spatial (vertical and lateral) differentiation and temporal (dynamic) resolution is required to meet EPA objectives.

Kruger (Washington State Department of Ecology).

- Kruger, D. M. 1979. Effects of point-source discharges and other inputs on water quality in Budd Inlet. DOE 79-11. Washington State Department of Ecology, Olympia, WA.

OBJECTIVE. WDOE conducted a receiving water study from 1976-1978 to provide more detailed information on Budd Inlet (Figure 5-2). The objective of the study was to determine the cause and effect of existing water quality problems and obtain data that could be used to evaluate pollution abatement projects planned for the Olympia area.

DESCRIPTION. A steady-state, 1-dimensional model was used to predict dissolved oxygen concentrations. The time factor represented the replacement time for Budd Inlet.

FORMULATION. A 1-dimensional model was used to describe the hydrodynamic and mass transfer processes in the horizontal direction. First order reaction rates were used to describe reactions that affect the dissolved oxygen concentration. Dissolved oxygen sources included in the model were Puget Sound waters, Capitol Lake inflow, and surface reaeration. Planktonic oxygen production and respiration were not included. Dissolved oxygen sinks included BOD loading from the Olympia sewage treatment plant and phytoplankton decomposition. For analysis the study area was divided into 15 segments of variable size.

STATUS. The model was applied to Budd Inlet and the results were variable. The predicted DO levels were slightly lower than the observed values. The difference between observed and predicted values appeared to be caused by phytoplankton oxygen production in excess of respiration, which was neglected in the model. Input to the model consisted of morphological data for the segments, salinity, temperature, diffusion coefficients, and oxygen demand. Other required information included deoxygenation rate, flow, and wind speed.

ADEQUACY. After initial calibration, the model appears to predict the general shape of the longitudinal dissolved oxygen profile accurately and predicts dissolved oxygen concentrations on the conservative side. From simulation results, causes of existing water quality problems were inferred. The model assumes that the entire water column is mixed.

TRANSFERABILITY. A program listing of the model is available in the reference and examples of input are also included. Data for this study were collected by WDOE.

APPLICABILITY. The model is applicable only to Budd Inlet, a minor region of Puget Sound, which can be characterized by a 1-dimensional representation. Improved description of the hydrodynamic processes would be required for use in other regions of Puget Sound. EPA requires greater temporal resolution than available in this model. This model is not adequate for general application in Puget Sound.

Yearsley (Environmental Protection Agency).

- Yearsley, J. R. 1973. A steady-state three dimensional diffusion model for Port Gardner - a subsystem of Puget Sound. EPA, Region 10, Seattle, WA.

OBJECTIVE. This model was developed to aid in the determination of the coefficients of eddy diffusivity for use in a steady-state diffusion model for dissolved oxygen. Many studies have been conducted to describe changes in eddy diffusivity coefficients as the scale of motion varies.

DESCRIPTION. Sulfite waste liquor (SWL) discharged by two pulp mills in Everett was used as a tracer during the study. The SWL has a long half-life and was considered as a conservative substance. Therefore, the observed distributions of SWL indicated the magnitude of the eddy diffusivity coefficients present. The coefficients of eddy diffusivity estimated from the SWL analysis were then used to verify a Fickian diffusion model for dissolved oxygen.

FORMULATION. The basic formulation of the model is the steady-state balance for a control volume for a conservative substance where dispersion is the only process. By appropriate transformations the 3-dimensional conservation equation can be reduced to a 1-dimensional system. Similarly, the conservation equations for BOD and DO can be simplified. Relaxation methods are used to solve the simplified 1-dimensional equations. The study area was divided into sections 900 m^2 by 10 m deep throughout the water column.

STATUS. This model has been applied to Port Gardner in the Whidbey Basin (Figure 5-2). Excellent data for the analysis were provided by water quality surveys conducted by state and federal regulatory agencies from 1962-1964. Data required for

the model include discharge rate of SWL, DO and BOD concentrations, rate constants for BOD decay, dilution of the waste plume, and boundary conditions at the control volume interfaces. A buoyant plume model developed by Baumgartner et al. (1971) was used to calculate dilutions and equilibrium levels. Eddy diffusivities were calculated from field measurements.

ADEQUACY. Results of the model show that the predicted concentrations of SWL and DO closely resemble the observed values. Therefore, the assumption that the eddy diffusivities for SWL are similar to those for DO is accurate. This model would only be applicable to areas where tidal dispersion was the dominant process. The results show the pollutant concentrations only for steady-state; time variations in concentration cannot be calculated. The eddy diffusivities must be empirically calibrated for each test location through field studies.

TRANSFERABILITY. Solutions to the conservation equations for the Port Gardner case were obtained on an IBM 370 computer. Convergence was attained after approximately 30 iterations and computer execution time was about 22 seconds.

APPLICABILITY. The formulation is based on a steady-state concept. To determine fluctuations of variables with time, a dynamic representation is required. The model also depends heavily on empirically determined information, so that it is site-specific. The model empirically determines diffusion coefficients for areas where tidal dispersion is the dominant process. This formulation is not adequate for general application to Puget Sound.

Water Resources Engineers, Inc. (Walnut Creek, California).

- Water Resources Engineers, Inc. 1975. Ecologic modeling of Puget Sound and adjacent waters. WRE 11930, OWRR C2044-X, EPA.

OBJECTIVE. This report summarizes a 2-year effort of mathematical model development and testing to develop assessment methodologies for water quality management decision making. Emphasis of the model development centered around the characterization of the hydrodynamics of Puget Sound and the prediction of water quality variables.

DESCRIPTION. The model employs a link-node network to represent the system. Combinations of submodels are used to describe six subsystems: the Central Basin, the Whidbey Basin, the Southern Basin, Hood Canal, Dyes and Sinclair Inlets; and an area between Bellingham and Anacortes (North Sound as shown on Figure 5-5). Model formulations consist of partial differential mass balance equations.

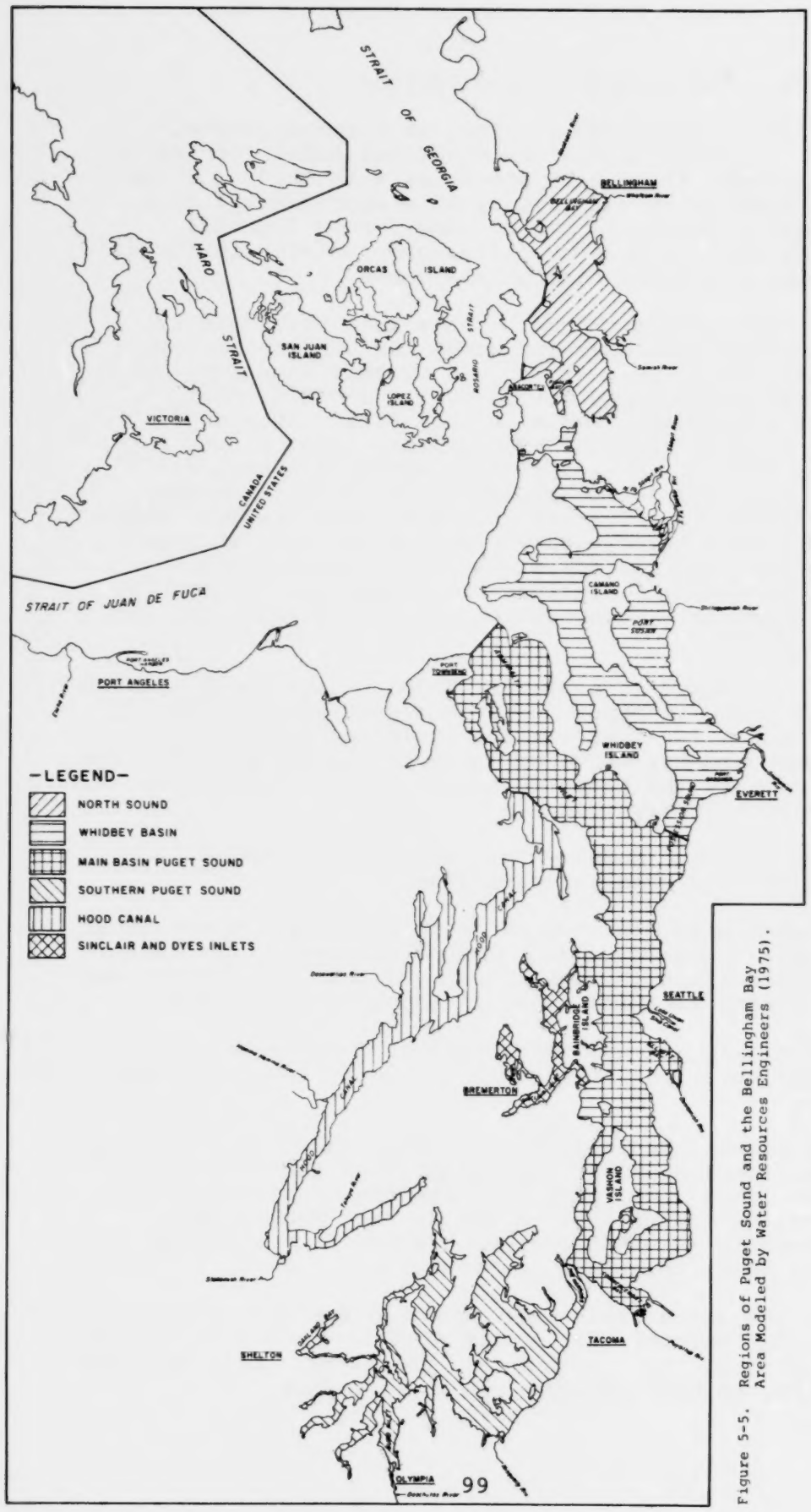

Figure 5-5. Regions of Puget Sound and the Bellingham Bay Area Modeled by Water Resources Engineers (1975).

FORMULATION. The submodels used include:

- Fjord Hydrodynamic Model - This is a steady-state, vertically 2-dimensional mathematical model for use in nonbranching, fjord-like estuaries with uniform flows. The bathymetry of the prototype is approximated by a rectangular channel. The driving forces for this submodel include density differences between inflow and ocean water and the tide at the mouth.

- Estuary Hydrodynamic Model - This is a horizontally 2-dimensional hydrodynamic model for use in shallow, branching estuaries. The fluid dynamic equations are 1-dimensional but are solved over a 2-dimensional network to simulate 2-dimensional flow. This model produces three types of hydrodynamic input to the water quality models: a steady-state hydraulics tape for long-term steady-state ecologic simulation; another steady-state tape for use in the dynamic ecologic model that utilizes steady-state circulation; and, a dynamic hydraulics tape for dynamic ecologic simulations. Inputs to the model include: geometry of the network, tidal stage data, evaporation rate, wind velocity, and system flows.

- Three-Dimensional Circulation Model - This model is also used to generate input to the ecologic models. Steady-state velocities over a tidal cycle, bathymetry, and regional geometry serve as input to the simulation. The model adjusts the flows to assure that continuity is satisfied at every node.

- Estuary Ecologic Model - This formulation models 22 biological and chemical variables.

The model predicts changes throughout a 3-dimensional link-node network. Steady-state, tidally averaged hydrodynamic data along with nutrients, light, food availability, oxygen, and various process rate kinetics serve as inputs to the model.

- Lake Ecologic Model - This model is a 1-dimensional ecologic water quality model for use in lakes or reservoirs.

- Finite Element Ecologic Model - This model is a vertical 2-dimensional steady-state formulation for stratified waters. This model also includes the 22 biological and chemical variables used in the Estuary model. The hydrodynamic input should be obtained from a finite element model to assure continuity.

Values of the 22 variables are computed for each section at each time step by solving the set of differential mass balance equations describing the ecological processes utilizing the predictions from the hydrodynamic models as inputs.

STATUS. The basic model has been applied to several locations including Lake Washington (WA); Lake Koocanusa (MT); Lake Whitney, Lake Garza-Little Elm, Lake Levingston, and Belton Reservoir (TX); Courtright, Wishon, and Lakeport Lakes (CA); Tocks Island (PA); San Francisco Bay; and Puget Sound. For application to Puget Sound, the area was divided into five main subregions: Puget Sound, Hood Canal, Southern Puget Sound, Whidbey Island, and Dyes and Sinclair Inlet. A link-node network was not established for the North Sound subsystem. Each subregion was treated separately and a combination of the described submodels was selected to simulate changes in each subregion. The model "packages" were calibrated against field observations of the prototype.

Data required to operate the model include initial concentration of all variables, tributary discharge and quality, meteorological data such as solar radiation, wind velocity, air temperature, and process rate coefficients. Region geometry and bathymetry are also required. The authors state that the model packages need further development to improve general applicability and the input data base for Puget Sound should be increased to produce more accurate model calibrations.

ADEQUACY. This model has proven to be a valuable tool in simulating water quality in past applications. In Puget Sound the model simulated basic natural phenomena. However, several problems with model calibration arose throughout the process. In the Fjord Hydrodynamic Model continuity was not satisfied when transferring computed flows to the ecologic model. The formulation involves an exponential function whose integral satisfies continuity only when the limits of integration are carried to infinity. The currents that are predicted from the hydrodynamic model are realistic from a hydrodynamic viewpoint but require fine tuning for use in the ecologic models. Manual adjustment of flow reversals is difficult for complex networks and the development of a "current" processor is advised.

A sensitivity analysis was performed on the process rate coefficients and waste inputs for Southern Puget Sound. DO and algal concentrations were selected as measures of the model's response.

TRANSFERABILITY. More data are needed for model calibration. Sufficient calibration data were available for DO total dissolved solids, and phosphate. These constituents have been sampled regularly throughout the Sound.

The effort required to apply the simulation model to Puget Sound would depend on the level of detail required. The basic components of the model are readily accessible and would require modification of some hydrodynamic modules.

APPLICABILITY. The combined use of submodels in this formulation allows for application to various regions of Puget

Sound. The link-node and finite element methodologies allow for variable "grid" size for improved resolution where necessary. Various biological and chemical parameters are modeled but sedimentation is not considered. Further calibration and data collection efforts are required, but the general formulation shows potential for meeting EPA's objectives.

Value of Existing Puget Sound Models as an EPA Waste Management Tool

A total of 15 different modeling investigations of various portions of Puget Sound have been reviewed in detail in this section. The purpose of the review is to determine if any existing models of Puget Sound can be adapted for use by EPA as part of their long-range study on developing comprehensive waste management strategies for the Sound. Each of the 15 investigations have been reviewed in terms of their theoretical formulation, status of development, adequacy of representation of the dominant physical processes, transferability, and applicability for meeting EPA's objectives. The following conclusions have been drawn:

- Two of the investigations (Barnes et al. 1957; Farmer and Rattray 1962) involve the physical oceanographic model of Puget Sound located at the University of Washington. This model, due to its extreme distortion, is not quantitatively valid for localized areas of interest, such as Elliott and Commencement Bays.

- Five of the developed models (Friebertshauser and Duxbury 1972; Pease 1980; Stevens, Thompson & Runyan, Inc. 1975; Winter et al. 1975; and Yearsley 1973) are strongly empirical in their formulation and would have very limited value as general, predictive tools.

- One of the models (Winter 1973) is an analytical power series solution of steady-state circulation in the surface layer of channelized geometries. This model is considered too restrictive for present needs and has become outdated by more recent work by Winter and his associates.

- One model (Kruger 1979) is limited to a 1-dimensional, steady-state solution of flow and dissolved oxygen in a portion of Budd Inlet. Again, this model is too simplified and restrictive for general application.

- Three models (Stewart 1982; Cokelet pers. comm.; and Seattle Metro 1983) are presently under development. The model by Stewart is semi-empirical and is being applied to the Duwamish River and Elliott Bay area. Although eventual use of this model in the Duwamish River area is of potential value to EPA, application to

other areas will be difficult due to its dependency on site-specific field observations. The model being developed by Metro utilizes a relatively crude, analytical approach and does not appear to hold value for EPA's program objectives. The model by Cokelet is a vertically averaged numerical model for calculating flows, currents, and tides in the horizontal 2-dimensional plane. It is under preliminary development for the Central Basin, and appears to be very similar to the model recently developed by Jamart and Winter (1978) (see discussion below).

- One modeling investigation (Crean 1978) involves application of a standard, explicit, 2-dimensional, finite-difference, vertically averaged circulation model to the Strait of Juan de Fuca and the Strait of Georgia for simulation of general tide and current patterns. There are numerous models of this type in existence and application on a general basis to Puget Sound would be severely limited due to the high cost of the explicit time-stepping integration scheme, especially for areas of great depth such as the Sound.

- One of the developed models (Jamart and Winter 1978) employs a unique approach in solving the time and space-dependent, 2-dimensional motion equations through a harmonic analysis utilizing Fourier transformations. The result is a very flexible technique which appears to accurately simulate complex tides and circulation with minimal cost, since the time variable is chosen independent of the other variables. A major limitation of this model, however, is in its assumption of vertical averaging of flows and currents. Thus, it is limited in its applicability to areas where stratified estuarine flows are weak or nonexistent. The model holds promise, however, for two types of applications of interest: a relatively crude, depth-averaged simulation of the entire Puget Sound to provide approximate tidal flows on a regional basis; and, refined applications in subregions of Puget Sound where vertical mixing is dominant over estuarine circulation, e.g., Dyes Inlet or Southern Puget Sound.

- A series of transport, water quality, and ecosystem models has been developed for Puget Sound (Water Resources Engineers 1975) for EPA. Two of the models suffer from the requirement of field observations to ensure that generated flows and currents are realistic of the prototype for layered estuarine-type circulation.

These models cannot be considered predictive. However, for well defined scenarios of transport dynamics (made possible through seasonal field data, for instance), they can conveniently provide compatible input to the developed water quality and

ecosystem models through which various waste disposal schemes could be examined. The value of adapting the Water Resources Engineers (WRE) models for the EPA model development program is discussed later in this report. Special consideration must be given to the availability of and/or additional requirements for field data which would be representative of average seasonal and critical conditions for waste assimilation in the Sound.

A third transport model developed by WRE (a link-node model), by nature of its pseudotreatment of horizontal motion (as well as being depth-averaged), must be very carefully calibrated and adjusted through comparison to field observations before confidence in its predictive ability can be achieved. Properly tested, however, this type of model could be a valuable tool for two general types of applications: a relatively crude, depth-averaged simulation of the entire Puget Sound to provide approximate tidal flows on a regional basis; and, refined applications in subregions of Puget Sound where vertical mixing is dominant over estuarine circulation.

In summary, none of the models in their present form meets management needs as outlined in Chapter 3. Major limitations include:

- Dimensionality - Many of the models use 1-dimensional formulations which represent over-simplified systems. In making water quality management decisions for Puget Sound, knowledge of vertical mixing and transport processes is required. Important lateral concentration gradients are lost in the "average" quantities produced by these models.

- Spatial Resolution - Some of the formulations utilize grids to break up the study area into workable units. Variable values calculated by the model represent average values over the entire grid element. Therefore, use of large elements leads to decreased spatial resolution. Many of the models lacked grid flexibility; the grid size could not be altered easily. To evaluate water quality management options, detailed information in certain areas (around waste inputs and other areas of interest) and general descriptions in others are required. Thus, lack of grid flexibility severely limits the applicability of some models.

- Site-Specific - Some of the models are site-specific. The assumptions and basic equations used in the models are only applicable to a certain area or water body type. Although these models may have limited value in application to small subsystems of Puget Sound, overall water quality management decisions would require a series of models for application to all subsystems of Puget Sound.

- Verification and Calibration - Many of the models lacked adequate calibration and verification. Before these models can be used to make water quality management decisions, the formulation must be verified and the coefficients must be calibrated for the area being analyzed.

Two of the models reviewed, however, warrant further investigation. The model developed by Jamart and Winter (1978) employs a unique solution technique which utilizes Fourier transformations. This technique is very efficient and flexible and appears to accurately simulate complex tides and circulation patterns in Puget Sound. The set of models developed by WRE (1975) utilizes a link-node system representation which has been successfully applied in several other areas. This set of models is complex, however, and would require considerable calibration before application to Puget Sound.

Prior to recommending application, a review is needed of other existing hydrodynamic models to determine whether one of these may be applicable to Puget Sound and require lower development costs. The following section is a brief presentation of several mathematical models which are available and could be applied to Puget Sound.

Models Developed For Other Areas

Brief Model Overview

This section presents the findings of a literature survey of other existing mathematical models for hydrodynamic simulations of estuaries, lakes, and oceans. Previous reviews of the state-of-the-art have been made by various authors, e.g., Hinwood and Wallis (1975a), Jirka et al. (1975), JAYCOR (1979), Najarian and Thatcher (1980), Pagenkopf and Fong (1980), and Najarian (1981). Some of the findings of these investigations have been incorporated into the present study. In addition, personal contacts with several individuals have been made to solicit opinions and more detailed information on the capabilities and limitations of certain models.

To facilitate discussion of the major findings of the model evaluations, models are grouped according to their dimensional treatment, i.e., 1-dimensional in the horizontal, 2-dimensional in the horizontal, 2-dimensional in the vertical, and 3-dimensional. Major model evaluation criteria were as described earlier in this chapter.

Since literally hundreds of mathematical models for hydrodynamic and water quality simulation exist, a coarse primary screening was required to eliminate models having the least relevance to the present study objectives. A major criterion

used was that models be well-documented, available in the United States or Canada, and if possible, be in the public domain. Table 5-2 presents the models selected for more detailed evaluation.

One-Dimensional Network Models

One-dimensional network models, although admittedly crude in terms of spatial representation, are of interest for possible application to certain subsystems of Puget Sound, such as Dyes and Sinclair Inlets, or Southern Puget Sound, during periods when the water column is approximately laterally and vertically mixed. The accuracy of 1-dimensional network models depends on whether the underlying assumptions of fully vertical and lateral mixing are met. Of further importance is the accurate computation of the dynamically varying flow field to avoid ambiguous dispersion concepts (i.e., steady state or tidally averaged).

According to Najarian and Thatcher (1980), there are at least 15 models which fit into the 1-dimensional network category. Many of these are modifications of the link-node approach developed by Chen and Orlob (1972), which is widely used in estuary simulation and has been previously applied to portions of Puget Sound (Water Resources Engineers, Inc., 1975). Another network formulation is the MIT Dynamic Network Model (MIT-DNM) resulting from several research projects at MIT (Harleman et al. 1977). Unlike the technique developed by Chen and Orlob, MIT-DNM is not a link-node formulation, but rather a network formulation wherein each element, or reach, of the network is of variable area.

The major differences between the above two models are in the incorporation of density-gradient effects and dispersion effects on mass transport. The MIT model includes the density gradient term in the longitudinal momentum equation, whereas the link-node model does not. The density gradient term allows representation of mass transport due to longitudinal salinity gradients within the estuary, which has been shown by Najarian and Thatcher (1980) to typically account for 5-10 percent of the mass transport. Typically in the link-node model, adjustments in Manning's "n" (bottom friction) must be made to artificially compensate for the lack of inclusion of the density gradient term. Thus, model "tuning" of coefficients becomes more critical in the link-node model.

Dispersion effects in the link-node model are purely a result of the numerical technique used and have no physical basis. The numerical dispersion results from the first order, explicit finite difference treatment of the advective transport terms. Further adjustments of the Manning's bottom friction coefficients must typically be made to compensate for the lack of user-control on the dispersion phenomenon. In the MIT model, a more sophisticated numerical method has been employed which is

TABLE 5-2. MODELS SELECTED FOR DETAILED EVALUATION

Model	Spatial Domain			Temporal Domain			Predictive Capability				Practicality		
	1-D[a]	2-D[b]	3-D[c]	Steady State	Tidally Averaged	Dynamic	Fully Prognostic	Diagnostic (Density)	Convective-Diffusion	Numerical Tech[d]	Users Manual	Status[e]	Relative Cost[f]
Chen and Orlob, 1972	N			x	x	x		x	x	EFD	x	PU	L
Harleman et al. 1977	N					x		x	x	IFD	x	PU	L
Leendertse, 1970		V				x		x	x	IFD	x	PU	M
Taylor and Pagenkopf, 1981		V				x		x	x	IFD	x	PRI	M
Wang and Connor, 1975		V				x		x	x	EFE	x	PU	M-H
Jamart and Winter, 1978		V				x		x		H		PRI	L
Blumberg, 1977		LE				x	x		x	EFD		PRI	M-H
Edinger and Buchak, 1979		LE				x	x		x	IFD	x	PU	M
Najarian et al. 1982		LE				x	x		x	IFD		PU	M
Norton et al. 1973		LE				x	x		x	EFD		PU	M-H
Street et al. 1977		LE				x	x		x	EFD		PRI	M-H
Wang and Kravitz, 1980		LE				x	x		x	IFD		PU	M
Wang, 1979		LE				x	x		x	EFE		PRI	M-H
Winter, 1973		S		x			x					PRI	L
Hurlburt and Thompson, 1980			LA			x		x		IFD		PRI	M
Wang and Connor, 1975			LA			x		x	x	EFE	x	PU	M-H
Blumberg and Mellor, 1978			LE			x	x		x	ESM		PRI	H
Leendertse and Liu, 1973, 1975			LE			x	x		x	EFD	x	PU	H
Sengupta et al. 1978			LE			x		x	x	EFD	x	PU	H
Sheng and Butler, 1982			LE			x	x		x	IDE		PU	M
Simons, 1972			LE			x	x		x	ESM		F	M-H
Swanson, in prep.			LE			x	x		x	ISM		PRI	M
Bennett, 1977			R			x	x		x	IFD		PRI	M
King, 1982			LE	x		x	x		x	EFE	x	PU	H
Huang, 1977			R			x	x		x	IFD		PU	M
Lick, 1976			R			x	x		x	IFD		PU	M
Lee et al. 1982			R			x	x		x	IFD	x	PU	M
Pearce and Cooper, 1981			FU			x		x		EFD	x	PU	M
Isaji et al. 1982			FU			x		x	x	EFD		PRI	M

[a] N=Network.

[b] V=Vertically Integrated, LE=Laterally Integrated Levels, S=Similarity Solution.

[c] LA=Layers, LE=Levels, FU=Continuous Functions, R=Rigid.

[d] EFD=Explicit Finite Difference, IFD=Implicit Finite Difference, EFE=Explicit Finite Element, IFE=Implicit Finite Element, ESM=Explicit Split Mode, ISM=Implicit Split Mode, H=Harmonic Decomposition.

[e] PU=Public Domain, PRI=Private Domain, F=Non U.S.

[f] H=High, M=Medium.

substantially free from numerical dispersion compared to the link-node model. The dispersion relationship incorporated into the MIT model accounts for the real physical effects of density-induced vertical stratification and turbulent shear effects on internal dispersion. Dispersion coefficients are assigned based on observed physical phenomena in the estuary, as opposed to artificial adjustments of bottom function, as in the link-node model.

Both the link-node model by Chen and Orlob and MIT-DNM are designed to handle most of the important water quality parameters, including phytoplankton biomass simulation. Either of these models could be applied with minor or no modifications to portions of the Puget Sound system which can be characterized adequately by a 1-dimensional network representation. However, according to the above discussion and findings presented in other reviews (Najarian and Thatcher 1980; Pagenkopf and Fong 1980), it is concluded that the MIT-DNM model is a superior model in all aspects in the category of 1-dimensional network models.

Two-Dimensional Vertically Averaged Models

Vertically averaged, 2-dimensional models have proved to be quite useful, especially in modeling the hydrodynamics and water quality of relatively shallow estuaries and lakes. Possible applications of such models for Puget Sound would include Bellingham Bay (North Sound), Dyes and Sinclair Inlets, and portions of Southern Puget Sound during periods when the water column is reasonably well mixed. The 2-dimensional models would be more appropriate than 1-dimensional network models if spatial resolution in the lateral direction (cross channel) is required. This might be the case when examining the local effects of a sewage discharge or waste source located in a relatively shallow and wide (2-dimensionally shaped) area. Additional applications would be required in areas where tidal flats are extensive.

A review of these models' applications, limitations, and general characteristics is given by TRACOR (1971), Jirka et al. (1975), Hinwood and Wallis (1975a, b), and Pagenkopf and Fong (1980). The crucial assumption of these models is the vertically well-mixed layer from the bottom to the free surface.

Over 50 models exist which fit into the 2-dimensional, vertically averaged class. Some of the more prominent models that have been widely used and publicized include those by Leendertse (1970), Wang and Connor (1975), and Taylor and Pagenkopf (1981). As pointed out by Jirka et al. (1975), most models of this type are quite similar in terms of physical formulation and mathematical refinement. Differences usually exist only with respect to the computational technique such as finite element vs. finite difference methods. For purposes of the present study, model selection has been based on:

- The model's prior performance in similar situations,
- Generality of the model for practical, realistic simulations.
- Sophistication of the numerical technique and resultant costs.
- Model availability/transferability.

Two models that are believed to best represent the state-of-the-art of generalized 2-dimensional, vertically-averaged, hydrodynamic-dispersion models are the MIT finite element model by Wang and Connor (1975), and the finite difference model by Taylor and Pagenkopf (1981). The model developed at MIT by Wang and Connor is one of the most widely used models of its type in existence. This model has the advantage of being flexible in grid size, but the disadvantage of high computing cost due to the explicit-type Courant limited time stepping technique. The model by Taylor and Pagenkopf has the advantage of moderate computing cost and the disadvantage of a fixed grid size. However, this limitation can be overcome somewhat by using a nested grid. Both models include the important physical processes of tides, wind stress, multiple discharges, Coriolis force, convective accelerations, and both have compatible convection-diffusion routines capable of simulating salinity, temperature, suspended solids, and general water quality constituents.

A major feature of the model by Taylor and Pagenkopf is the capability to simulate the effects of alternate flooding and drying of tidal flats, both in the hydrodynamic and water quality calculations. This feature is rarely found in similar models, and has been thoroughly and successfully tested in a number of areas including Flushing Bay, (NY); Jubail Industrial City Harbor, Saudi Arabia; Anclote Anchorage, and Biscayne Bay, (FL) (Taylor and Pagenkopf 1981). Areas exhibiting substantial tidal flats in Puget Sound include, but are not limited to, extreme portions of Southern Puget Sound, Nisqually Reach, Skagit Bay, Port Susan, and Bellingham Bay.

Based on the factors considered above, either the MIT finite element model by Wang and Connor (1975), or the finite difference flooding and drying model by Taylor and Pagenkopf (1981) would be adaptable to use in Puget Sound. Choice of the model would depend on the requirements of a specific application.

Two-Dimensional Laterally Averaged Models

When viewing Puget Sound as one large, integrated system, a reasonable characterization of flow is that of an interconnected network of long, deep, and narrow passageways. In turn, these

passageways primarily exhibit strong stratification due to salinity and temperature differences which control vertical mixing and the distribution and long term net transport of contaminants. A 2-dimensional approach, oriented along the vertical and longitudinal axes of the estuary, is justified because of the narrow and deep nature of the system. The advantages of such a model are manyfold. First, such a model could provide system-wide information on interbasin exchange of flow and contaminants as well as overall net mass transport and flushing. Second, such a model is desirable in providing the proper boundary conditions for any subsequent sub-basin model application (which may involve a more detailed 3-dimensional approach). Third, for relatively moderate costs, a 2-dimensional laterally-averaged model would allow consideration of the dominate vertical and longitudinal hydrodynamic and mixing processes occurring in Puget Sound. The 2-dimensional laterally averaged models, however, do require the assumption of uniform lateral mixing in the cross channel direction.

There are a number of 2-dimensional, laterally-averaged models in the literature, several of which were reviewed in this study. Model limitations that were common were: lack of branching capabilities, high computational costs, and extensive modifications required for application to Puget Sound. Three models are presented below which could be beneficially applied to Puget Sound.

Edinger and Buchak (1978). A model for application to deep reservoirs and lakes has been developed by Edinger and Buchak (1978) for the COE. This model, called "LARM," can realistically portray the effects of variable widths as well as depths on the hydrodynamic characteristics of the system. More significantly, LARM allows a larger time step to be used in the computations. This capability greatly reduces the computation time otherwise required in hydrodynamic model application to Puget Sound. LARM has been verified on a number of large reservoir systems, including Sutton Reservoir in West Virginia (Edinger and Buchak 1979) and Center Hill Lake in Tennessee (Gordon 1980).

Although this model is considered one of the more advanced in the literature, several modifications would be required before application to Puget Sound. The required modifications would include:

- Incorporation of the additional density modifiers (salinity and suspended solids) that occur in estuaries.

- Specification of proper sources, sinks, and settling velocities for suspended solids.

- Incorporation of a branching or network capability

such that multiple interconnecting reaches can be simulated (i.e., the entire Puget Sound).

- Incorporation of desired water quality variables and associated sources, sinks, and decay functions in the conservation of mass equation.

- Incorporation of appropriate ocean boundary conditions to drive the model.

The decision to select the LARM model and incorporate the above features involves a trade-off between allowable development costs and the availability of other, more appropriate, models.

Wang (1979). Recently, Wang (1979) developed a finite element model of 2-dimensional stratified estuarine flow. This model employs a triangular grid scheme in the vertical, which has the advantage of flexibility in allowing greater resolution where needed, and cruder representation in areas exhibiting noncritical flow behavior (i.e., deep layers). Wang (1979) emphasizes the strength of his approach in analyzing net circulation in estuaries with irregular bottom topography when accurate boundary conditions are specified. The finite element technique used is explicit, and thus requires a small time step. Therefore, applications to deep estuaries could become prohibitive due to significant computation time. Additional modifications would also be necessary before application to Puget Sound. These include development of a branching capability for simulating multiple channels, and incorporation of temperature, suspended solids, and other desired water quality variables in the appropriate equations along with proper sources, sinks, and decay rates.

Najarian et al. (1982). A series of models for estuary applications was begun by Blumberg (1977), with subsequent modification and improvement by Wang and Kravitz (1980) and Najarian et al. (1982). The above investigators have extensively studied the importance of properly assigning the coefficients of momentum viscosity and mass diffusivity in a 2-dimensional, laterally-averaged model. These authors have demonstrated the sensitivity of the model response to the above parameters as affected by the stratification and net circulation in an estuary.

Wang and Kravitz (1980) improved Blumberg's model by adopting a semi-implicit scheme which allowed increases in the time step by one to two orders of magnitude. This feature is especially critical for model applications in deep water systems such as Puget Sound. Further modifications were made by Najarian et al. (1982). They incorporated nonlinear convective terms in the momentum equation, and adjusted ocean boundary condition specifications to account for longitudinal velocity and salinity gradient approximations at these boundaries. In addition, the original single-channel model was extended to

include multiple, interconnected branches. Within each channel, the model physics are identical to the single-channel model, and at the junctions the continuity and salt conservation equations are modified to provide for the mass and salt exchange.

Blumberg (1977) applied his model to the Potomac Estuary to investigate the net circulation and salt distribution in the Potomac. Applications of the modified model were also made by Wang and Kravitz (1980) to the Potomac Estuary, resulting in successful simulation of the stratification and destratification of the water column due to wind stress. The results from these two applications indicate that the model appears very promising as a means of addressing circulation and water quality in stratified estuaries.

Najarian et al. (1981) applied the branching model to the Chesapeake Bay and its major tributaries to investigate effects of fresh water flows and ocean boundary conditions on estuary salt distributions. The model successfully reproduced observed trends in bay-wide salinity distributions.

Of all existing 2-dimensional laterally-averaged models, the model by Najarian et al. (1981) probably offers the most appropriate technique for application to Puget Sound. Advantages of this model include:

- It is based on sound theory and research.
- It is capable of representing most of the major physical processes in estuaries (however, temperature, suspended solids, and water quality variables are not included).
- It utilizes an efficient semi-implicit numerical scheme.
- It has been verified on numerous occasions against both analytical solutions and actual estuaries.
- It was developed under public funding (Maryland State Power Plant Siting Board, National Science Foundation, and NOAA) and is therefore readily available.

Necessary further modifications required for Puget Sound would include:

- Incorporation of the additional density modifiers, temperature, and suspended solids, along with the proper sources, sinks, and decay or settling rates.
- Incorporation of desired water quality variables and associated sources, sinks, and decay functions.

The above modifications are not major, in that the bulk of the model theory and coding would remain unchanged.

Three-Dimensional and Layered Models

For purposes of the Puget Sound model development program, 3-dimensional models are of primary interest in providing more detailed representation of a particular basin within the system, which may exhibit important lateral processes as well as vertical and longitudinal behavior. A primary example would be the Central Basin, which receives wastes from multiple discharges along its shores, is relatively wide in certain areas, and exhibits complex net transport such as around Vashon Island. Another example is the Whidbey Basin, which has both shallow and deep areas, exhibits large lateral and vertical density gradients, and receives major freshwater inputs and waste loadings.

Fully 3-dimensional and layered models have been the subject of considerable attention and research over the last decade. Although still a developing field, there are a number of models which have been applied with moderate success to estuarine, oceanic, and lacustrine systems. The difficulty in this type of modeling is in the specification of the internal turbulent momentum transfer and mass diffusivities, which ideally are calibrated with field observations, thus making availability of adequate prototype data an important consideration. An additional factor of great importance is the relative cost of running a given model, which is directly dependent on the numerical scheme used.

For purposes of discussion and comparison, 3-dimensional models can be separated into four main categories: layered, leveled, rigid-lid, and continuous function. Each type of model has certain advantages and disadvantages, primarily related to treatment of the vertical processes of momentum and mass exchange, as well as numerical stability of the time integration.

Layered Models. The philosophy of layered models follows closely the ideas involved in producing the vertically-averaged 2-dimensional models discussed earlier. There are, however, four additional processes that need to be incorporated into the general description of the circulation and mass transport. Layered models require at least one boundary (interface) where vertical mass and momentum transfer occurs due to advective and diffusive processes. Thus, at this interface there is vertical advection which is determined by: the strict application of the 3-dimensional continuity equation; momentum transfer through interfacial shear stresses from one layer to the other; mass transfer through advection; and mass transfer through diffusive processes. Conceptually, layered models differ from vertically-averaged models only by their mathematical representation of the transfer processes occurring at layer interfaces.

Multi-layer models have been developed by Hurlburt and Thompson (1980) and Wang and Connor (1975). Both of these models have two layers, where the density of each layer must be specified and remains constant throughout space and time. Thus, these models do not treat density-induced transport due to salinity and temperature effects. In layered models, as opposed to leveled models, the depth of the interface is spatially and temporally varying. Therefore, it is very difficult to impose a 3-dimensional continuity equation at this interface with the intent of computing the vertical velocities. Although interfacial mass transfer is discussed in the Wang and Connor (1975) model and provisions are made to account for it, its presence in this model is irrelevant, since temporal variations of density in the two layers are ignored. This implies that there is no salt transfer from the bottom layer to the top layer. In summary, therefore, in the Wang and Connor (1975) model, only interfacial momentum transfer is incorporated; the remaining processes that are active at this boundary are simply discussed in the model development.

Leveled Models. A number of investigators have developed multi-level models for estuarine, oceanic, and lacustrine applications (Leendertse and Liu 1973, 1975; Simons 1972; Blumberg and Mellor 1978; Sengupta et al. 1978; Lee et al. 1978; Swanson in prep.; King 1982; and Sheng and Butler 1982). Of these models, the 3-dimensional discrete element model developed by Sheng and Butler (1982) shows the greatest potential for adaptation to Puget Sound. This model is an extension of earlier models developed by Sheng et al. (1978) and Sheng (1980). Special computational features included in the model have led to a very efficient and versatile 3-dimensional model suitable for long term simulations. The model also includes both temperature and salt in the density and mass conservation computations. The model has been compared to analytical solutions and physical experiments for tidal flows. It has been applied to Lake Erie for wind stress simulation, and to the Mississippi Sound for simulation of tidal and wind induced currents. Further testing of the model is underway for specific applications to sediment transport simulation.

Sheng and Butler (1982) point out that a wide variation exists among the various forms of the vertical turbulence stability functions determined empirically by various investigators, and suggest that the appropriate stability function is dependent on the type of numerical scheme used and the nature of the water body under study. Thus, site-specific testing of empirical relationships for vertical eddy diffusivity will probably be required for any model application to Puget Sound. Further research is underway to develop a second-order closure model of internal turbulence which is less dependent on empirical information (Sheng and Butler 1982).

Necessary data for calibration of the empirical relation ships and coefficients are required. Computation requirements

have been minimized by the incorporation of an implicit integration scheme and vertical and horizontal coordinate and transformation schemes into the code.

It is believed that the above model by Sheng and Butler (1982) offers the best overall 3-dimensional technique for purposes of EPA's Puget Sound model development program. The only further modifications required would be incorporation of additional water quality parameters and appropriate sources, sinks, and decay functions.

Rigid-Lid Models. Rigid-lid models have been developed by several investigators, including Bennett (1977), Huang (1977), Lick (1976), Sheng et al. (1978) and Lee et al. (1982). The "rigid-lid" approach essentially involves elimination of surface gravity wave effects (tides) from the governing motion equations. These models are primarily intended for simulation of large-scale, relatively low frequency forcing phenomena such as wind stress and surface heat flux, which dominate large lake circulation. The one advantage of this approach is that the computational costs have been minimized by the ability to choose a large time step. However, since more efficient numerical schemes for 3-dimensional free-surface models are now available (Sheng and Butler 1982), there is no longer an advantage to choosing a rigid-lid approach. Furthermore, it is extremely doubtful that a rigid-lid model can adequately simulate a water body such as Puget Sound where circulation and mass transport are dominated by the short period (12 hours) free-surface tidal wave forces.

Continuous Function Models. All 3-dimensional models discussed previously divide the vertical water column into discrete steps of finite thickness (layers or levels). Alternatively, continuous function models allow for a continuous description of the dependent variables in the vertical direction. This is accomplished by allowing the dependent variables to be expanded in terms of a series of time and spatially varying coefficients and a set of mathematical functions which are continuous over the vertical. This approach has been the subject of numerous modeling studies, but only recently have models been developed which offer general capability for estuarine and coastal application. Two models of primary note are those by Pearce and Cooper (1981) and Isaji et al. (1982). The model by Pearce and Cooper (1981) employs a series of cosine funtions to define the vertical expansion series while the model by Isaji et al. (1982) utilizes Legendre polynomials.

The major advantage of continuous function models is in their ability to simulate rapid vertical gradients in horizontal velocities such as surface current shear induced by a wind stress. Continuous function models, therefore, are of primary interest in simulation of wide open, coastal, lake, or ocean systems where wind effects are important and where the primary

interest is in the trajectory of a surface pollutant, such as an oil spill. At present, continuous function models have not been developed which are also capable of prognostic simulation of the interactive effects of density gradient induced flows (temperature and salt) as well as the 3-dimensional mass transport of contaminants.

Based on the above findings, the model by Sheng and Butler (1982) is the most appropriate technique in the category of 3-dimensional and layered models for application to Puget Sound.

Value of Existing Models

The objectives of the modeling effort for Puget Sound are to identify depositional areas for contaminated solids (fate of solids) and to determine retention time of dissolved pollutants and suspended solids (interbasin transfer, overall circulation patterns, fate of solids). Although major concern is focussed on urbanized embayments because of known or suspected pollution-related impacts on beneficial uses, an overall Puget Sound model is necessary to supply important general information on net circulation, mass transport, and boundary conditions to drive more detailed subarea models.

Fifteen model applications to various portions of Puget Sound were reviewed in the second section of this chapter. The purpose of that review was to determine if any existing models of Puget Sound could be adapted by EPA as part of their long-range study on developing comprehensive waste management strategies for the Sound. It was concluded that none of the existing models were adequate for this purpose because they are limited by either dimensional or spatial treatment, empirical dependence, or lack of generality. None of the models applied to Puget Sound adequately describes overall circulation patterns, fate of solids, and interbasin transfer on a Sound-wide basis.

It is evident that a model must be developed to provide system-wide information for use in more detailed formulations and to assess the sensitivity of model results to variations of important driving variables and boundary conditions. One option is to modify a model already developed for Puget Sound. Two of the modeling studies were examined in more detail and compared to the present state-of-the-art for estuary hydrodynamic and water quality modeling. These included the model by Jamart and Winter (1978) and the set of models by Water Resources Engineers (1975), which included a steady state fjord hydrodynamic model by Winter (1973).

The model by Jamart and Winter (1978) utilizes a unique approach in solving the time- and space-dependent 2-dimensional (depth averaged) motion equations through a harmonic decomposition employing Fourier coefficients. The result is a model with a very flexible finite element grid and very efficient

simulation costs, since the time step can be chosen independently from all other variables. Upon closer examination, however, it is found that this technique, in comparison with other existing techniques, has several limitations. One major limitation is in its assumption of vertical averaging of flows and currents, thus limiting its applicability to areas where stratification is weak (shallow, well-mixed areas). A second major limitation is that it has been designed for purely periodic tidal motion, and cannot simulate more complicated time series events such as caused by wind, storm surges, high river discharge, etc. It is vital that, for future application to various water quality and waste management studies, any selected model be sufficiently general to handle a wide variety of prototype scenarios. Additional assumptions made in this model are omission of Coriolis forces, wind stress, and all non-linear terms of the motion equations, such as the convective accelerations. In addition, the model has never been coupled to the mass conservation equation, and its ability to adequately conserve mass is in question.

The hydrodynamic models developed by WRE (1975) for Puget Sound include: a vertically 2-dimensional steady-state fjord circulation model for simplified geometries (Winter 1973); a 3-dimensional field current processor which interpolates and smooths data into a 3-dimensional continuous (steady-state) form; and a vertically-averaged link-node estuary model which uses multiple-branched 1-dimensional channels to provide pseudo-simulation of 2-dimensional horizontal flows. Upon closer examination, it is determined that the first two models are severely limited in their general applicability due to their dependence on prototype field data. For example, it was reported by WRE (1975) that the fjord model by Winter (1973) did not conserve mass, and calculated currents were required to be arbitrarily adjusted until mass conservation was achieved. Similarly, the field current processor involves considerable smoothing and adjustment of the 3-dimensional steady-state currents in order to achieve reasonable mass continuity in the water quality modules. Neither of these approaches can be considered predictive, in that the simulations that can be achieved are only representative of the specific period during which the field data (upon which the model is based) were collected.

The depth-averaged estuary link-node model developed by WRE (Chen and Orlob 1972), was discussed in detail under the review of existing 1-dimensional models developed for Puget Sound. The findings of this review indicate that the link-node model involves a considerable approximation of the true physical processes of dispersion and mixing within an estuary. The bottom friction coefficients in each channel must be manually adjusted to compensate for the lack of consideration of turbulence-induced and density-inhibited longitudinal and vertical dispersion effects.

A second option is to adapt to Puget Sound a model that has been developed for other areas and comparable conditions. Ideally, the model would be a 3-dimensional representation of the entire system; however, the costs of such a model would be prohibitive, especially for long-term transient simulations. Fortunately, a 2-dimensional, laterally-averaged approximation of the Sound as a whole is justifiable because of the generally narrow and deep nature of Puget Sound. This type of model could be used to describe mass transport, net circulation patterns, and boundary conditions for more detailed models of subareas.

The state-of-the-art model review summarized in the previous section identified the model by Najarian et al. (1981) as the optimum existing technique for application to Puget Sound as a whole. Modifications that would need to be made for Puget Sound are not major. The model by Sheng and Butler (1982) is recommended for adaption to the Central Basin. It is a 3-dimensional leveled model that has a horizontal coordinate transformation scheme that provides flexibility in grid layout. Other key features of this model include an implicit scheme for the external free-surface mode and a vertical coordinate transformation scheme which provides the same number of continuous layers throughout the system. The model should be capable of predicting circulation patterns, mixing processes, solids transport and accumulation, and other water quality variables on a local basis. Specific areas (e.g., urbanized embayments) may be considered on a smaller scale basis by adjusting the grid elements and time steps.

Field Data Requirements and Availability

This section describes the kinds of data needed for development and application of water quality models for Puget Sound. In addition, the currently available sources for hydrodynamic and water quality data are summarized.

Field Data Requirements

Prototype field data are required for proper calibration and verification of models. The necessity of collecting additional field data as part of a modeling study of Puget Sound will entirely depend on the adequacy and completeness of existing data sources. Ideally, two completely independent sets of prototype data should be available: one for model calibrations, and one for model verification. It may be sufficient to use different seasons of the same year, but use of noncontiguous periods is a more rigorous test of the model.

In general, the following types of data are required for both model calibration and verification.

Meteorological Data.

- Wind speed and direction on a 6- to 12-hour frequency at several locations throughout the study area.

- At the same locations, parameters are needed for calculation of surface heat flux, including incoming solar radiation, air temperature, and relative humidity.

- Records of precipitation and evaporation on a daily basis.

- Barometric pressure data on a 6- to 12-hour frequency.

Boundary Conditions Data.

- Tidal records are required at the entrances of Admiralty Inlet and Deception Pass from the Strait of Juan de Fuca for the duration of the model simulation period (days-weeks). It is essential that time synchronization of the data be accurate due to the short phase lags characteristic of the area. Similar data are also required for Bellingham Bay, since it is a separate system off the Strait of Georgia.

- Temperature and salinity distribution over depth and time are required at the same locations to enable accurate specification of heat and salt fluxes through the ocean boundaries. Frequencies of data records should be adequate to define behavior during a complete tidal cycle, and long term behavior over several days-weeks.

- Specifications of water quality conditions are probably not critical at ocean boundaries, since these boundaries are chosen far from the major contaminant sources. Estimates of constituent concentrations of these locations can probably be made from a limited data set.

- Fresh water inflows from all major rivers and streams are required on an approximately daily basis.

In Situ Hydrodynamic Data.

- Tidal records at several locations spread throughout the Puget Sound system are required for comparison to model results. Again, it is critical that time synchronization of the data be accurate, since the study area represents a very small portion of a very long period (tidal) wave.

- In situ (Eulerian) current measurements are desirable for comparison to model computed currents. Locations of current meter arrays must be carefully selected due to the high cost of deploying and maintaining deep water

moorings. The most critical locations for current measurements are in areas where flow phenomena are likely to be most complex. These areas include the vicinities of major sills where upwelling and downwelling occur, and in the channels around Vashon Island where complex net circulation is known to occur. Duration of current measurements should be adequate to define both short term tidal frequencies, as well as residual currents caused by lower frequency phenomenon (winds, density flows, atmospheric pressure, etc.).

- Vertical temperature and salinity profiles should be available at various locations along the longitudinal axis of the Sound's major sub-basins to define the spatial and time varying distribution of the density structure. This type of data is considered critical in achieving meaningful model calibration and verification, since the density structure is closely associated with vertical mixing rates and long term net transport throughout the system. Ideally, the temperature-salinity profiles should be collected as synoptically as possible. This type of information should be available on a monthly-seasonal basis to indicate long term changes in the density structure.

Water Quality.

- Depending on the study area, detailed information on major waste loadings is required in terms of flow rates and contaminant concentrations.

- The above information is also required for the major rivers and streams in the area.

- *In situ* monitoring of water quality data is required, with inclusion of DO, BOD, and suspended solids at a minimum.

- For simulation of suspended solids or sediments, field and laboratory tests should be made to determine grain size distributions, specific gravity, and settling characteristics of the material under investigation. These tests must obviously be made on a site-specific basis.

The field data requirements discussed above are primarily focused on the calibration and verification of a 2-dimensional, laterally-averaged model of the entire Puget Sound system. Field data requirements for testing individual basin models parallel those for the 2-dimensional laterally-averaged model. However, for local, site-specific water quality studies, sub-basin models may require specialized data requirements. These programs are more appropriately designed after the specific objectives of the site-specific studies are defined.

Available Field Data for Puget Sound

A substantial amount of data is available for many physical/chemical parameters in Puget Sound, but it is not in an organized, comprehensive format. Several agencies in the State of Washington have collected field observations. Many of these studies were oriented towards describing specific water quality problems and therefore generated detailed measurements for limited areas. There has been little past effort to combine the data sets to form a comprehensive data base and index for general use. The local agencies most frequently involved with data collection on Puget Sound include: Metro; EPA; WDOE; the University of Washington; and NOAA, including the National Weather Service. Other agencies that collect data on an occasional, site-specific basis are WDF, the U.S. Army COE, and various engineering and oceanographic consulting firms. Table 5-3 summarizes the major available data sources.

General Studies and Data Bases. The University of Washington continually conducts studies to measure water quality parameters in Puget Sound. Most projects are limited to a specific study area, but many different regions of Puget Sound have been considered. Data have been collected throughout all of the sub-basins of Puget Sound, the North Sound, and up into the Strait of Juan de Fuca and the San Juan Island Passages. The data are usually held by the project researchers and are not entered into a central data base. Collias (1970) indexed all of the University of Washington data through 1966. This index was updated by Evans-Hamilton Inc. (Cox pers. comm.). These volumes represent the most comprehensive data collection available. Typical parameters recorded in the index include depth, date, location, temperature, salinity, DO, and less frequently, dissolved inorganic phosphate, sulfite waste liquor, nitrate or nitrite-nitrogen, silicate, and alkalinity. Data sources are listed for each entry in the index. The data were also plotted and put into an atlas for quick reference (Collias et al. 1974). Collias and Andreeva (1977) compiled a bibliography of references on Puget Sound, including many quantitative studies.

The physical model at the University of Washington has served as an aid in qualitatively describing the hydrodynamic processes in Puget Sound and locating problem areas such as regions of possible pollutant accumulation and stagnation areas. The model, however, is not capable of generating accurate numerical data for use in calibration and verification of a mathematical mode. The physical model could best be used as a guide in future research efforts.

NOAA sponsored a series of studies (MESA) and publications on Puget Sound from 1976 to present. NOAA currently publishes an updated bibliography and data catalog that describes the data base (U.S. DOC 1980a). Measurements include currents, trace metals, suspended sediment, salinity/temperature/depth (STD) or conductivity/temperature/depth (CTD), phytoplankton, wind, and

Table 5-3. Available Data Sources

Region	Currents	Tides	STD	Transport	Nutrients	DO	Suspended Solids	Meterological Data
North Sound		U.S. DOC 1982 U.S. DOC 1980b	Collias 1970		Collias 1970 WDOE	Collias 1970 WDOE		NCC[1]
Strait of Juan de Fuca	U.S. DOC 1980b U.S. DOC 1980a	U.S. DOC 1980b U.S. DOC 1982	Collias 1970 U.S. DOC 1980a WDOE		Collias 1970 U.S. DOC 1980a WDOE	Collias 1970 WDOE	U.S. DOC 1980a	NCC U.S. DOC 1980a
Strait of Georgia	U.S. DOC 1980b	U.S. DOC 1980b U.S. DOC 1982					U.S. DOC 1980a	
San Juan Island Passages	U.S. DOC 1980b U.S. DOC 1980a	U.S. DOC 1982 U.S. DOC 1980b	Collias 1970 U.S. DOC 1980a WDOE		Collias 1970 WDOE	Collias 1970 WDOE	U.S. DOC 1980a	NCC
Admiralty Inlet	Cox et al. 1981 U.S. DOC 1980a	U.S. DOC 1982 U.S. DOC 1980b	Collias 1970 U.S. DOC 1980a WDOE	Barnes and Ebbesmeyer 1978	Collias 1970 WDOE	Collias 1970 WDOE		NCC
Whidbey Basin	Cox et al. 1981	U.S. DOC 1982	Collias 1970 WDOE	Barnes and Ebbesmeyer 1978	Collias 1970 WDOE	Collias 1970 WDOE		NCC
Central Basin	Cox et al. 1981	U.S. DOC 1982	Collias 1970 U.S. DOC 1980a WDOE	Barnes and Ebbesmeyer 1978 Ebbesmeyer and Barnes 1980	Collias 1970 Collias and Lincoln 1977 WDOE	Collias 1970 WDOE		NCC
Hood Canal	Cox et al. 1981	U.S. DOC 1982	Collias 1970 WDOE		Collias 1970 WDOE	Collias 1970 WDOE		
Southern Basin	Cox et al. 1981	U.S. DOC 1982	Collias 1970 WDOE		Collias 1970 WDOE	Collias 1970 WDOE		NCC

[1]National Climatic Center (NCC)

biological information. The data catalog contains all data received by the Environmental Data and Information Service of NOAA through April, 1980. A recent reorganization has transformed this group into the National Environmental Satellite, Data, and Information Service (NESDIS). Data are available by formal written request to NESDIS.

NOAA maintains several data service centers on a national basis, including the National Oceanographic Data Center, National Climatic Center, and the National Geophysical and Solar-Terrestrial Center. These data centers collect data nationwide from several sources, including all NOAA projects and the National Weather Service. These centers can retrieve data and reformat the information (graphs and plots) to meet user requirements. Data are available by formal written request.

Metro sponsored a series of reports entitled "Puget Sound Interim Studies" (Duxbury 1976). The Central Basin was selected as the study area for most of the field measurements. Topics include: physical characteristics; water quality studies; nutrient observations; phytoplankton productivity; dye and drogue tracer studies; heavy metals concentrations; and biological information on fish, zooplankton, and intertidal life.

EPA has been collecting water quality data from several sources including Metro, WDOE, and the University of Washington. The data are being compliled in a STORET computer base. Most of the observations are site-specific, and the data are far from comprehensive (only selected data have been entered into the system). For example: data from Metro are primarily coliform measurements; EPA data are site-specific and a majority of the observations are taken at locations of pulp mill activity; and field observations made by WDOE are for smaller waterways in the Puget Sound area. Variables included in the computer base are trace metals, hydrocarbons, turbidity, conductivity, DO, pH, and salinity.

Synoptic Data Bases. Few synoptic or comprehensive data bases exist at the present time. There have been attempts to collect and index all data for general use. The NODC data base, University of Washington Index, MESA catalog, and the current meter index by Cox et al. (1981) are the only comprehensive data bases available. A substantial amount of data has been collected by various agencies in informal or unpublished form which, when organized, could offer a relatively continuous data base or significant addition to existing comprehensive sources.

CURRENTS. Cox et al. (1981) compiled an index to current observations in Puget Sound from 1908 to 1980. Variables indexed include locations, date, depths, and method of measurement. The index includes approximately 50 years of current observations of one day or longer taken at approximately 300 sites throughout the Sound (Whidbey Basin, Admiralty Inlet, Central Basin, Southern Basin, and Hood Canal). Most current

measurements in the index were taken at several depths to give the vertical current variation.

The National Ocean Survey (NOS) (U.S. DOC 1980b) conducted a circulatory survey of the Puget Sound approaches (Strait of Juan de Fuca, Haro and Rosario Straits, and the Strait of Georgia) from the fall of 1973 to the fall of 1976. The survey consisted of seven phases and considered parameters such as currents, tides, and salinity. Meteorological data such as wind speed and direction, sea-level pressure, and air temperature were also recorded. Historical current and tide data for the area taken prior to this study are included in this report.

The MESA data catalog lists several current meter stations located in the Strait of Juan de Fuca, the San Juan Island passages, Admiralty Inlet, and specific locations within the Central Basin (West Point and the Tacoma Narrows).

One area lacking current meter data is the North Sound (Bellingham Bay). The NOS survey located two current meter stations at the entrance to the bay (U.S. DOC 1980b). Data on currents in the bay may be available on a project-specific basis, but studies have not been identified at the present time.

TIDES. The NOS generates yearly tide tables that tabulate tidal current, and high and low water predictions (U.S. DOC 1982a and 1982b). Reference stations within the study include Admiralty Inlet, Deception Pass, Rosario Strait, San Juan Channel, and the Narrows in Washington, and Rack Rocks, British Columbia, Canada, for tidal currents. Reference stations for high and low water predictions include Port Townsend and Seattle in Washington, and Victoria, British Columbia. Corrections are given for several other locations within Puget Sound and the approaches based on the reference station values.

The NOS Puget Sound Approaches survey (U.S. DOC 1980b) located several tide stations within the study area (San Juan Island passages, Strait of Juan De Fuca, and Strait of Georgia). All stations were occupied for at least 29 days while principal stations were operated for periods of 1 year or more. Historical tide data were reviewed in this publication and shown to be quite extensive.

SALINITY/TEMPERATURE/DEPTH. The index to oceanographic data (Collias 1970), the index update (Evans-Hamilton Inc., Cox pers. comm.), and the NOS Puget Sound Approaches survey (U.S. DOC 1980b) all have compiled STD measurements. The atlas of physical and chemical properties of Puget Sound (Collias et al. 1974) has plotted and contoured temperature, salinity, and density throughout the four major sub-basins in Puget Sound and into the Strait of Juan de Fuca.

The index tabulates measurements at depth for all areas within the study region. The NOS survey concentrates on the

Strait of Juan de Fuca, San Juan Island passages (Haro and Rosario Strait) and the Strait of Georgia. These two data bases will offer a good set of independent data compilations for the Puget Sound approaches.

The MESA data catalog lists STD and CTD measurements for several locations, including the Central Basin, Admiralty Inlet, Tacoma Narrows, Strait of Juan de Fuca, and the San Juan Island passages. These data are available from NODC by written request.

METEOROLOGICAL DATA. The meteorological parameters of interest include wind speed, direction, and barometric pressure. The National Weather Service has set up several stations around Puget Sound to measure meteorological variables, such as temperature, precipitation, wind, atmospheric pressure, and cloud cover. Most of the data are recorded at airport stations, which take measurements on an hourly basis. The National Weather Service has not collected data from on-water sites in Puget Sound. Station locations on the east side of Puget Sound offer a continuous record from Olympia to Bellingham. There are no stations operated in the Bremerton or Hood Canal areas, and only a few stations in the Puget Sound approaches (Port Angeles and Bellingham in Washington, and Victoria and Patricia Bay in British Columbia, Canada).

Data from the National Weather Service are available at several locations including the Seattle Public Library, National Climatic Center (NCC) and the state climatologist at Western Washington University.

The MESA data catalog shows several stations in the Strait of Juan de Fuca where wind data have been collected. These data could compliment the National Weather Service data base for this area.

PHYSIOGRAPHIC DATA. McLellam (1954) conducted an area and volume study of Puget Sound. Puget Sound was divided into 57 regions and the volume of water within 10-fathom increments and the area for each region was calculated. Area was determined by planimetering with a compensating polar planimeter. Volume calculations were made by plotting graphs with square nautical miles versus depth as coordinates for each region.

WATER QUALITY VARIABLES. The water quality variables of potential importance in modeling studies are DO, nutrients, suspended solids (accumulation and settling rates), and BOD. Of the variables listed, DO has been recorded much more frequently.

Collias et al. (1974) and Collias (1970) compiled DO and nutrient concentrations observations for all regions of the study area. DO was measured for almost every entry in the index. Nutrient concentrations (dissolved inorganic phosphate and nitrate or nitrite-nitrogen) were measured at few stations

and do not represent a comprehensive data base. No measurements of BOD were indexed.

The MESA data catalog lists nutrient concentrations measurements for a few stations in the Strait of Juan de Fuca. The nutrients being measured were not described in the catalog. These observations could supplement the indexed nutrient data, but the data base is still far from comprehensive. Trace metals concentrations and suspended sediment were also compiled in the MESA catalog for stations located in the Strait of Georgia, the San Juan Island passages, and the Strait of Juan de Fuca.

Several reports in Metro's Puget Sound Interim Studies discussed water quality studies in the Central Basin. Topics covered in these reports included: water quality studies in the vicinity of Metro sewage outfalls (measurements such as temperature, salinity, density, DO, light transmittance, and pH); nutrient observations (inorganic phosphate; dissolved silicate, nitrate, and ammonia; temperature; salinity; and DO); and heavy metals concentrations in the water column, biota, and sediments.

WDOE conducts water quality monitoring at 44 stations throughout Puget Sound (Figure 4-1) on a monthly basis during spring, summer, and fall. The data are stored in computer files and are kept at the WDOE office at Tumwater. The parameters monitored are listed in Table 4-3.

FRESHWATER DISCHARGE. Many rivers and streams flow into Puget Sound, but 80 percent of the freshwater influx is represented by 11 of the largest rivers. USGS publishes a water-data report for every water year (USGS 1978). This report contains records of stage, discharge, and water quality of streams (including specific conductance, pH, DO, water temperature and sediment discharge) on a daily basis for all gauged and sampled water bodies. Water discharge is given as daily mean values, and minimum and maximum discharges.

INTERBASIN TRANSPORT. Few studies have been conducted to measure the water transport rates between or though sub-basins of Puget Sound. Barnes and Ebbesmeyer (1978) estimated mean transport rates for Admiralty Inlet, Whidbey Basin, Deception Pass, Central Basin, and Colvos Passage. Values presented were the average of the transport rates in the upper and lower layers and were based on analysis of current records and water properties. Transport rates have not been calculated for the other sub-basins in Puget Sound.

SILL ZONE PROCESSES. Data are required in the vicinity of sill zones to adequately test model predictions of sill zone processes. Ebbesmeyer and Barnes (1980) conducted a series of field observations and tests using the physical model to qualitatively describe processes at the landward and seaward sill zones of the Central Basin. This study serves as the starting point for future research.

Water reflux to the Central Basin at the entrance sill (Admiralty Inlet) was estimated by Barnes and Ebbesmeyer (1978). Reflux of water back into Puget Sound greatly affects pollutant concentrations and residence times and is an important sill zone process. No reflux estimates have been calculated for other areas in Puget Sound.

Summary

The objectives of the modeling effort for Puget Sound are to identify depositional areas for contaminated solids (fate of solids) and to determine retention time of dissolved pollutants and suspended solids (interbasin transfer, overall circulation patterns, fate of solids). Although major concern is focussed on urbanized embayments because of known or suspected pollution-related impacts on beneficial uses, an overall Puget Sound model is necessary to supply important general information on net circulation, mass transport, and boundary conditions to drive more detailed subarea models.

Fifteen model applications to various portions of Puget Sound were reviewed in the second section of this chapter. The purpose of that review was to determine if any existing models of Puget Sound could be adapted by EPA and WDOE as part of their long-range study on developing comprehensive waste management strategies for the Sound.

Major limitations of models that have been or are currently being applied to Puget Sound include:

- Dimensionality - Many of the models use 1-dimensional formulations which represent over-simplified systems. In making water quality management decisions for Puget Sound, knowledge of vertical mixing and transport processes is required. Important lateral concentration gradients are lost in the "average" quantities produced by these models.

- Spatial Resolution - Some of the formulations utilize grids to break up the study area into workable units. Variable values calculated by the model represent average values over the entire grid element. Therefore, use of large elements leads to decreased spatial resolution. Many of the models lack grid flexibility. Detailed information in certain areas (around waste inputs and other areas of interest) and general descriptions in others are required, thus, lack of grid flexibility severely limits the applicability of some models.

- Site-Specificity - Some of the models are site-specific. The assumptions and basic equations used in the models are only applicable to a certain area or water body type.

- Verification and Calibration - Many of the models lacked adequate calibration and verification. Before these models can be used to make water quality management decisions, the formulation must be verified and the coefficients must be calibrated for the area being analyzed.

It was concluded that none of the existing models were adequate for this purpose because they are limited by either dimensional or spatial treatment, empirical dependence, or lack of generality. None of the models applied to Puget Sound adequately describes overall circulation patterns, fate of solids, and interbasin transfer on a Sound-wide basis.

It is evident that a model must be developed to provide system-wide information for use in more detailed formulations and to assess the sensitivity of model results to variations of important driving variables and boundary conditions. One option is to modify a model already developed for Puget Sound. Two of the modeling studies were examined in more detail and compared to the present state-of-the-art for estuary hydrodynamic and water quality modeling. These included the model by Jamart and Winter (1978) and the set of models by Water Resources Engineers (1975), which included a steady state fjord hydrodynamic model by Winter (1973). The model developed by Jamart and Winter (1978) employs a unique solution technique which utilizes Fourier transformations. This technique is very efficient and flexible and appears to accurately simulate complex tides and circulation patterns in Puget Sound. The set of models developed by WRE (1975) utilizes a link-node system representation which has been successfully applied in several other areas. This set of models is complex, however, and would require considerable calibration before application to Puget Sound.

A second option is to adapt to Puget Sound a model that has been developed for other areas and comparable conditions. Ideally, the model would be a 3-dimensional representation of the entire system; however, the costs of such a model would be prohibitive, especially for long-term transient simulations. Fortunately, a 2-dimensional, laterally-averaged approximation of the Sound as a whole is justifiable because of the generally narrow and deep nature of Puget Sound. This type of model could be used to describe mass transport, net circulation patterns, and boundary conditions for more detailed models of subareas.

The state-of-the-art model review summarized in the third section of this chapter identified the model by Najarian et al. (1981) as the optimum existing technique for application to Puget Sound as a whole. Modifications that would need to be made for Puget Sound are not major. The model by Sheng and Butler (1982) is recommended for adaption to the Central Basin. It is a 3-dimensional leveled model that has a horizontal coordinate transformation scheme that provides flexibility in grid layout. Other key features of this model include an implicit scheme for the external free-surface mode and a vertical coordinate transformation scheme which provides the same number of continuous layers throughout the system. The model should be capable of predicting circulation patterns, mixing processes, solids transport and accumulation, and other water quality variables on a local basis. Specific areas (e.g., urbanized embayments) may be considered on a smaller scale basis by adjusting the grid elements and time steps.

A substantial amount of data for use in circulation modeling is available for many physical/chemical parameters in Puget Sound, but it is not in an organized, comprehensive format. Several agencies in the State of Washington have collected field observations. Many of these studies were oriented towards describing specific water quality problems and therefore generated detailed measurements for limited areas. There has been little past effort to combine the data sets to form a comprehensive data base and index for general use. The local agencies most frequently involved with data collection on Puget Sound include: Metro; EPA; WDOE; the University of Washington; and NOAA, including the National Weather Service. Other agencies that collect data on an occasional, site-specific basis are WDF, the U.S. Army COE, and various engineering and oceanographic consulting firms.

Chapter 6

TRANSPORT AND FATE OF POLLUTANTS

Introduction

Information on water circulation in various regions or subareas of Puget Sound is required to understand where and how pollutants are distributed in Puget Sound. An effort is made in Chapter 5 to evaluate the ability of existing modeling efforts to describe circulation in Puget Sound. It is inappropriate, however, to assume that circulation patterns alone adequately describe processes linking the discharge of pollutants to their ultimate distribution in the physical environment. As pollutants are moved with the water mass, other processes influence the distribution and physico-chemical fate of pollutants within the water mass.

Chemical compounds enter Puget Sound from both point and nonpoint sources, including: rivers, atmospheric fallout, surface runoff, sewage treatment plants, industrial dischargers, and stormwater discharges. Sources of mass loading to Puget Sound were discussed in Chapter 4.

Except for localized areas, Puget Sound water quality usually meets the state's water quality standards. However, many contaminants are not included in the standards, and are not routinely monitored either in effluent or the ambient waters. Konasewich et al. (1982) list 183 organic compounds and 37 inorganic contaminants identified in Puget Sound water, sediments and biota. Malins et al. (1982a) identify several hundred compounds found in only three sediment stations (two in Commencement Bay and one in Elliott Bay). Metro's sampling program has shown the presence of approximately 1,800 compounds, most of which are still unidentified (Galvin pers. comm.). Many of these compounds are likely to be naturally occurring, or substances not known to cause adverse affects, but some may be hazardous. In addition to the large number of contaminants, a number of physical, chemical and biological processes may determine the ultimate fate of each compound.

Processes Affecting Transport and Fate

What happens to a pollutant as it enters Puget Sound depends on whether the pollutant is in a dissolved or particulate state. Some of the processes which influence the distribution and fate of a pollutant include the physical processes of adsorption, dissolution, sedimentation, and resuspension; the

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chemical processes of speciation, flocculation, chemical precipitation, diffusion, volatilization, photolysis, reduction/oxidation, and hydrolysis/hydration; and the biological processes of bioaccumulation, biotransformation, and biodegradation. Some of these processes are particularly important at the site of discharge because of the complex chemical reactions that occur as pollutants in freshwater (precipitation, riverine discharge, or wastewater discharge) encounter the chemical properties of marine water.

Adsorption

Heavy metals readily adsorb to particulate matter and, thereby, are removed from the dissolved state. Jackim and Lake (1978) have noted that adsorption also may be an important transport process for organics which have low solubility in water. Adsorption to particulate matter significantly changes the effects of currents and gravity on the distribution of pollutants.

Dissolution

Dissolution describes the movement of a compound into the dissolved state. It has been well established that the majority of pollutants in an aquatic environment can be found in the sediment rather than in the water column or biota (Cross and Sunda 1978). Most of the pollutants in the sediments are adsorbed or in a precipitate state. Very little is known about the rate of dissolution. Pollutants adsorbed to sediments or to suspended particulates perhaps are unlikely to undergo dissolution unless the concentration of dissolved material drops significantly from that during the adsorption period. Dissolution from precipitated deposits could be a significant process if the concentration of dissolved matter varies significantly over time.

Sedimentation

Sedimentation is the settling out of particulate matter due to the force of gravity. Sedimentation is a significant factor in the transport of pollutants because of the tendency for most pollutants to be adsorbed to particulate matter. The settling rate of a particle is a function of its specific gravity, size, shape, and water current force vectors. The distance that a particle will be transported from the point of introduction depends on its settling rate, water depth, and water velocity.

Resuspension

Even though the sediment comprises the largest compartment for storage of most pollutants, the length of the storage period depends on the rate of resuspension of the particulate matter comprising the sediments. Resuspension occurs by a variety of anthropogenic or natural processes. Major sources of resuspension include dredging, current scouring, and bioturbation (burrowing activities of benthic organisms).

Speciation

Speciation is a particularly important process relative to heavy metal ions that can occur in more than one valence state, e.g., copper, chromium, iron, manganese, mercury, tin, and antimony. Speciation is highly influenced by the chemistry of the receiving water. Reviews (e.g., Singer 1973; Rubin 1974; Wiley 1976, 1978; Baker 1980) of fate, bioavailability, and toxic effects of dissolved heavy metals have emphasized great variation in activity resulting from the tendency of the different dissolved species of heavy metal ions to form chemical associations with a variety of inorganic and organic compounds. Most ligands have the capacity to bind a variety of metals and ions. Competition for binding may be influenced by the species of heavy metal and their respective ion activities and stability constants.

Flocculation

Flocculation is the process of particulate matter coming together in a loosely organized aggregate mass (floc). It is a very important phenomenon when freshwater is discharged into saline water. Avnimelech et al. (1982) have shown that marine algae and suspended particulate matter in freshwater discharges readily combine to form flocculent matter. The fate of these aggregations is significantly different from that of the particles comprising the aggregate. The floc presents a larger surface area and different density and is therefore affected differently by currents and gravity. Flocculation alters the particles' availability to filter-feeding organisms in the water column. Curl (1982) noted that organic floc formation in the Duwamish River estuary provided a mechanism for removal of potentially toxic trace metals from the water column, thereby reducing toxicity to pelagic organisms but increasing the potential for bioaccumulation by benthic suspension and detritus feeders.

Chemical Precipitation

Chemical precipitation is probably important only on a localized scale and for certain pollutants because it requires that the loading of a pollutant in the dissolved state exceed the specific saturation level of that pollutant. Dissolved

iron, for example, may be rapidly removed from the water column by flocculation and precipitation (Holliday and Liss 1976), but the importance of precipitation is a function of flushing rate.

Diffusion

Diffusion is the passive spreading of a pollutant due to a decreasing concentration gradient. Diffusion may be important in areas with minimal water movement and in interstitial water in the sediments. Diffusion is a function of concentration gradients and is probably orders of magnitude less important than active transport caused by currents. The diffusion rate influences the rate of dissolution.

Volatilization

Volatilization is the flux of materials from the water surface to the atmosphere. Volatilization is a function of the vapor pressure of the pollutant and the relative concentrations in the water and atmosphere. It is also influenced by turbulence and temperature in the air and the water. Volatilization may result in removal of pollutants from the Puget Sound Basin, or may result in transport to a different location in the Sound. This redistribution depends on atmospheric circulation patterns and precipitation (fog, rain, or snow).

Photolysis

Photochemical reactions may occur through several mechanisms, depending on compound structure. They may also be either direct (the compound absorbs light directly) or indirect (other substances absorb light and react with the compound). Photolysis is most important in upper water layers which receive the most light. Photochemical processes may also form oxidants which react with pollutant compounds.

Reduction/Oxidation

Reduction has been infrequently reported as an important process, and can be either a biological or nonbiological process. It is most frequently reported in reactions where chlorine atoms in organochlorine compounds are replaced by hydrogen (Callahan et al. 1979). Oxidation is a chemical reaction in which oxygen atoms are added to the compound, or electrons are lost, thereby changing the state of the compound.

Hydrolysis/Hydration

Hydrolysis and hydration may also affect chemical states. Hydrolysis may be affected by pH, and generally results in

acquisition of a hydroxyl group and loss of another portion of the compound. Hydration, in contrast, results in addition of a water molecule to the compound through a reversible reaction. This generally results in a compound having properties different from the parent compound, which may affect transport pathways.

Oxidation/reduction and hydrolysis may all affect a compound, resulting in speciation, i.e., variation in chemical states of a compound. Chemical state is a very important factor in fate and transport processes because various states differ widely in stability, ability to adsorb to particulates, or potential to bioaccumulate. Some states are also more toxic than others. For this reason, determination of a compound's presence is often not sufficient unless its state is also known.

Bioaccumulation

Bioaccumulation is the uptake and retention of foreign substances (xenobiotics) by organisms. Bioaccumulation of toxic compounds can have adverse ecological effects. This process is especially important for lipophilic chemicals. Chemical concentrations tend to be nonuniformly distributed between organs of an individual organism and also vary between species. Compounds with higher chlorine content tend to be bioaccumulated more strongly. Bioaccumulation may occur through either skin/gill uptake, directly from the water, or through dietary intake.

Biotransformation and Biodegradation

Biotransformation/biodegradation reactions occur primarily in the sediments as a result of microbial enzyme reactions. The rate of transformation is dependent on concentration of both pollutant and microbial population, and transformation has been noted to occur more rapidly in areas where chronic pollution exists.

Available Data

As most compounds react with the environment in several ways, it is not practical or cost effective to research all potential interactions and effects. However, in many cases chemicals of similar structure behave similarly, and behavior can be predicted for a class as a whole; from this information, potentially hazardous pollutant groups can be identified.

Pollutants considered here include: the 126 found on the EPA priority pollutant list, polychlorinated dibenzofurans, petroleum hydrocarbons, and particulates. Particulates are often naturally occurring, but are considered as pollutants in this study because: 1) particulates in high concentration may have deleterious effects on the beneficial uses of an area; and

2) pollutants often adsorb to particulates, therefore, particulates play a significant role in transport and fate of these substances. Properties, fates, sources and information gaps are discussed for each of these groups below.

In interpreting the following information, a note of caution is warranted. Most monitoring efforts have addressed conventional pollutant parameters. Others have looked at the EPA priority pollutants to a minor degree. The priority pollutants were chosen on a nationwide basis because of their frequency of occurrence, chemical stability, amounts produced, and availability of standards and measurement (Silva 1981). There are a number of industry-specific pollutants which do not have enough national recognition or prominence to be included on the EPA priority pollutant listing, but which, nevertheless, may profoundly impact localized areas of Puget Sound because of high regional concentration. Few measurements have been regularly made for "nonconventional parameters" in effluent of many discharges, but absence of data should not be interpreted as absence of a problem, and concentrations in sediment, biota and water must be determined before possibility as a hazard can be dismissed.

Pesticides and Derivatives

Pesticides are generally considered of environmental concern because many are very toxic, persistent, and tend to bioaccumulate. These include: DDT and its metabolites, DDD and DDE; aldrin; endrin and endrin aldehyde; chlordane; heptachlor and heptachlor epoxide; acrolein; three hexachlorocyclohexane isomers; three endosulfan compounds and isomers; isophorone; TCDD; and toxaphene.

Sittig (1980) discusses health impacts for each compound. Callahan et al. (1979) and Konasewich et al. (1982) discuss properties and fates for all EPA priority pollutant pesticides. Chapman et al. (1979) describe design of monitoring studies for these compounds and review Metro effluent concentrations (Chapman et al. 1982a). Malins et al. (1982a) discuss pesticide levels in sediments and biota for various areas of Puget Sound.

DDT, DDD and DDE

Properties and Fates. All of these pollutants are persistent, bioaccumulative, essentially nonvolatile, and toxic. Adsorption is a major fate process for DDT and its metabolites, and all have a strong tendency to adsorb to sediment; this tendency is increased with increasing salinity. Bioaccumulation is also considered an important fate for all three compounds. Uptake of DDT by fish occurs primarily via the gills, and there is little or no evidence of food chain magnification (Konasewich

et al. 1982). Depuration rates are slow. DDT is metabolized to DDD and DDE by marine organisms, and DDE is the predominant form in biota. However, Puget Sound biota have greater relative amounts of DDT than have been found in other aquatic environments, possibly indicating that metabolism in Puget Sound is much slower (Konasewich et al. 1982).

Biodegradation/biotransformation is important for ultimate loss of DDT, and a slow but important process for DDD and possibly DDE as well (Callahan et al. 1979). Photolysis, hydrolysis and volatilization are less important. In strongly basic conditions DDT may convert to DDE (Konasewich et al. 1982). Oxidation is probably not important.

Sources and Distribution. Except for rare occasions, use of DDT has been banned in the United States since 1972, but concentrations in Puget Sound and biota remain high. Konasewich et al. (1982) review toxicity data, summarize DDT, DDD and DDE levels observed in Puget Sound sediments and biota, and discuss possible effects in Puget Sound. They note that highest concentrations occur in Elliott and Commencement Bays, indicating localized input, although it is not determined whether it is ongoing or residual contamination. All three compounds have been shown to exist in Metro West Point effluent, and are considered category 1 pollutants (the most important for sampling) by Chapman et al. (1979).

DDT, DDD and DDE are considered to be category 1 compounds (contaminants of concern) by Konasewich et al. (1982), based on their toxicity, distribution and possible ecological effects.

Over the long term, lack of use should result in a decline in concentrations, but there is little observable decline at present.

Information Gaps.

- A higher than normal DDT/DDE ratio exists in Puget Sound. The reason is unclear. Pesticide metabolism in Puget Sound sediments has been little studied.
- If metabolism studies indicate contamination is presently occurring, sources are not well identified.
- Accurate information on trends, persistence, and effects of these compounds in Puget Sound is lacking.

Chlordane and Heptachlor

Properties and Fates. Chlordane is extremely toxic; its use has been banned since 1978. It is classified as a Restricted Use Pesticide by EPA, and can be purchased and applied only by a certified pesticide applicator under certain limited conditions (Frandsen pers. comm.). Usage has thus been reduced. Several fates may be important, including volatilization,

adsorption to sediments and bioaccumulation. No information is available on oxidation; hydrolysis is not considered important. Photolysis may be of some importance. Bioaccumulation is an important aquatic fate and concentration factors can be quite high. Little information is available on biotransformation. Although it is known to be slow, it may be an important process for ultimate degradation (Callahan et al. 1979).

Heptachlor is also extremely toxic and classified as a Restricted Use Pesticide (Idaho Cooperative Extension Service 1981). Usage has therefore been reduced. The major aquatic fate process is rapid hydrolysis which results in a half-life of 1-3 days. Some photolysis and volatilization may occur. Adsorption is probably an important process, but no data are available. Heptachlor has a strong tendency to bioaccumulate, and can also be transformed into heptachlor epoxide (also toxic) or reduced to chlordine. Transformations occur slowly in relation to hydrolysis (Callahan et al. 1979).

Sources and Distribution. Chlordane levels noted in Puget Sound biota and sediments are generally low; chlordane does not appear widely dispersed. Highest levels were observed in the sediments of Commencement Bay, although fish liver samples from Elliott Bay occasionally showed relatively high levels (Konasewich et al. 1982).

Heptachlor has been occasionally observed in sediment and fish liver samples from Elliott and Commencement Bays, but it is uncertain whether it is a hazard (Konasewich et al. 1982). Callahan et al. (1979) indicate heptachlor has been measured in West Point treatment plant effluent, and recommend water sediments and biota be tested for its presence. Other sources are probably primarily nonpoint in origin, including rivers and stormwater runoff.

Konasewich et al. (1982) classify chlordane and heptachlor as category 2 contaminants (those for which an ecological hazard evaluation could not be provided).

Information Gaps.

- Information on locations and concentrations appears to be limited.
- Many information gaps exist concerning fates and chemical reactions.

Aldrin, Dieldrin, Endrin, Isophorone, and Hexachlorocyclohexanes

Properties and Fates. Important aldrin fate processes include biotransformation, volatilization, bioaccumulation and indirect photolysis. Biotransformation to dieldrin is probably the dominant process, and it occurs rapidly enough that bioaccumulation of aldrin through the food chain probably is not

significant. Volatilization half-lives in aquatic systems are only a few days. Adsorption to sediments may have some importance, and will eventually remove it from aquatic systems if biological processes do not (Callahan et al. 1979). Use of aldrin was banned in the United States in 1974 (Frandsen pers. comm.). Levels should therefore be decreasing.

Dieldrin, unlike aldrin, is persistent and considered by some to be one of the more nonbiodegradable chlorinated pesticides. Important fate processes include adsorption to sediment, bioaccumulation and volatilization. Adsorption and subsequent settling is likely to be important. Bioaccumulation is considered moderate to significant. Some data indicate biotransformation may occur. Dieldrin was also banned in 1974 (Frandsen pers. comm.).

Endrin fates in aquatic systems are not well known. Photolysis and biotransformation occur, but rates are not known. Bioaccumulation appears to be a significant process, and can occur through both food and water. Hydrolysis is not considered significant. No information is available on adsorption of either endrin or endrin aldehyde to sediments or biota (Callahan et al. 1979). Endrin was banned in 1979 (Frandsen pers. comm.).

Information on isophorone is limited. It is moderately soluble and likely to remain in the water column until transformations occur. Adsorption, volatilization, and bioaccumulation are not considered to be important processes.

Hexachlorocyclohexane isomers include lindane. In general, these compounds do not accumulate; and photolysis, oxidation, and hydrolysis are not important. Adsorption is an important process for transport to the sediments, and biotransformation/biodegradation is considered the most important fate process. Transformations are favored in aerobic, biologically rich environments. Use of lindane is currently under review (Frandsen pers. comm.).

Sources and Distribution. Pesticide sources are likely to be primarily nonpoint, either through riverine input, runoff, or atmospheric input.

Aldrin, dieldrin, isophorone and the hexachlorocyclohexane isomers (including lindane) have also been detected in Metro West Point effluent (Chapman et al. 1979). Konasewich et al. (1982) note that aldrin, dieldrin, endrin, and lindane have all been detected in Puget Sound, and classify aldrin, dieldrin, and endrin as category 5 compounds (those which are toxic but for which there is minimal information on distribution or levels). They classify lindane as a category 2 contaminant (one for which an ecological hazard evaluation could not be provided).

Analyses for aldrin in sediment and biota are reported (Brown, in Konasewich et al. 1982), but aldrin is metabolized to

dieldrin, which tends to be more persistent, and there is little information available on dieldrin levels.

Information Gaps.

- There is a general lack of information on pesticide distribution or levels in Puget Sound sediments and biota. Aldrin, dieldrin, endrin, and hexachlorocyclohexane appear to be of more immediate concern than some, because they have been noted in sediments and biota and/or treatment plant effluent. Callahan et al. (1979) recommend water, sediment, and biota near the outfall sites be tested for these compounds.

Other Priority Pollutant Pesticides

Properties and Fates. A number of pesticides considered as priority pollutants by EPA have not been observed in the limited number of samples tested. These include acrolein, the endosulfans, toxaphene, TCDD, and heptachlor epoxide. Properties and fates for these compounds are therefore covered only briefly.

Acrolein appears to be lost to aqueous environments quickly, with a half-life generally less than a day. The primary fate process appears to be hydration to a compound that is readily biotransformed. Photolysis, oxidation, and volatilization may possibly be important, but bioaccumulation and adsorption do not appear to be important processes (Callahan et al. 1979).

Data concerning TCDD are very incomplete, although adsorption and bioaccumulation appear to be important processes. Biotransformation may be important over long time periods, and photolysis will be important if reactive substrates are available (Callahan et al. 1979). TCDD is formed as a by-product during synthesis of polychlorinated phenols and their products, and is among the most toxic compounds known.

Data concerning endosulfan compounds are also incomplete. Hydrolysis is probably important, and adsorption, at least for the isomers, appears important. Bioaccumulation does not appear significant for the isomers, but no data are available for the sulfate. Biotransformations may be potentially important (Callahan et al. 1979).

Toxaphene is very stable in aerobic systems, but undergoes loss of its chloride content in anaerobic environments. Adsorption to particulates, sedimentation, and bioaccumulation appear to be important processes (Callahan et al. 1979). Existing stocks can be used until 1986, but because it was banned in 1982, usage should decrease (Frandsen pers. comm.).

Heptachlor epoxide is resistant to chemical and biological transformations, and a half-life of several years is probable. Biotransformation is slow, but possibly an important fate process. Moderate adsorption and bioaccumulation also occur. Little information on photolysis or volatilization is available. Oxidation and hydrolysis are not important processes (Callahan et al. 1979).

Sources and Distribution. Chapman et al. (1979) did not list these as being present in Metro West Point effluent, and they have not been listed by Konasewich et al. (1982) as having been observed in Puget Sound water, sediments, or biota.

Information Gaps.

- It is not clear whether these compounds are actually absent or merely undiscovered due to lack of sampling.

Polychlorinated Biphenyls

Although polychlorinated biphenyls (PCBs) are no longer manufactured in the United States, they are considered to be one of the most widely distributed pollutants and the most predominant contaminant of Puget Sound sediments (Konasewich et al. 1982). The primary producer, Monsanto Company, marketed a number of PCB mixtures under the Aroclor trademark, distinguishing the compounds by number (the first two digits indicating the parent compound as a biphenyl, the second two indicating the percent chlorine by weight). Of 209 possible PCB compounds, approximately 100 compounds and isomers have been detected in commercial compounds, and 7 of the aroclors are on the EPA priority pollutant list.

Information on health effects is given by Sittig (1980). Callahan et al. (1979) and Konasewich et al. (1982) provide fate data; Konasewich et al. (1982), Malins et al. (1982a), and Dexter et al. (1981) discuss PCB compounds in Puget Sound.

Properties and Fates

Properties and fate data for PCBs have been fairly well researched, and are summarized below. A detailed discussion of properties, structure, and fate processes, along with an extensive reference list, is given by Callahan et al. (1979) and Konasewich et al. (1982). Recommendations for monitoring these compounds are given by Chapman et al. (1982a), although these data conflict with Chapman et al. (1979), and to some extent with Callahan et al. (1979) as well.

Individual PCB compounds vary widely in their properties according to the number and position of the chlorine atoms. However, they all have a low water solubility, high dielectric

constant and low vapor pressure, and are generally thermally stable and inert.

Environmental distribution of PCBs is somewhat selective because lighter compounds are more likely to volatilize. Compounds in the atmosphere are similar to Aroclors 1242 or 1016; those in sediments approach the composition of Aroclor 1254, and those in biota tend to be heavier and more chlorinated, similar to Aroclor 1260.

The aquatic fate of an Aroclor varies widely depending on the compound. Photolysis may result in destruction of the heavier PCBs. Volatilization is an important transport mechanism, but it is depressed by the presence of organic solids. Biotransformation and biodegradation (the only proven natural destruction mechanisms for PCBs) are important only for compounds having less than four chlorine atoms. For these compounds, it appears to be the dominant fate process, and results in significant destruction and transformation.

Adsorption to particulate matter is generally rapid (Callahan et al. 1979). Because of their low solubility, in natural systems the majority of PCB compounds are adsorbed to sediments. The tendency for adsorption increases with degree of chlorination, water salinity and organic content, and with decreased particle size of the absorbant.

Bioaccumulation is generally rapid, and biomagnification occurs as well (Mearns pers. comm.). Bioaccumulation is heavily dependent on lipid levels in organisms. Uptake in lower trophic level aquatic organisms appears to be primarily by direct uptake from the water, whereas, dietary intake appears more important in PCB uptake by higher trophic organisms such as seals (Konasewich et al. 1982).

Adsorption and subsequent sedimentation is probably the most dominant fate process for PCBs within Puget Sound (Konasewich et al. 1982). Many sediments exceed the maximum levels of 500 ppb recommended by Pavlou et al. (1978 in Dexter et al. 1981), and levels of up to 400 ppm in the sediments and up to 500 ppm in fish liver have been measured. Known PCB levels and mean total concentrations in Puget Sound sediments and biota have been summarized by Konasewich et al. (1982), but no concentrations were detected in water or suspended matter above the detection limits of 0.5-1.0 parts per trillion (ppt) and 2-4 ppb, respectively.

Dexter et al. (1981) also summarize known PCB levels in sediments for Puget Sound areas. Highest concentrations were observed in the Duwamish River and Elliott Bay sediments (Goldberg 1979). Areas known to have especially high concentrations include Commencement Bay/Hylebos Waterway (the highest concentration of Aroclor 1242), the Duwamish River/Elliott Bay, and

Sinclair Inlet (Pavlou et al. 1976; Dexter et al. 1981; Riley et al. 1981).

There is also evidence that some microbial degradation occurs in aerobic sediments, but no evidence of it in anaerobic sediments. Anaerobic environments may therefore serve as long term sinks for PCBs (Elder 1976 in Konasewich et al. 1982). Sediments in Elliott and Commencement Bays have higher levels of di- and trichlorobiphenyls (the lower chlorinated compounds) than Budd or Case Inlets, indicating that areas of higher anaerobic conditions exist in the bays. It therefore does not appear that biodegradation plays a significant role in removal of PCBs from the Sound (Konasewich et al. 1972).

Sources and Distribution

Potential PCB sources include leaks from transformers, hydraulic systems, heat exchangers, capacitors, and compressors (Sittig 1980; Konasewich et al. 1982). Polychlorinated biphenyls have also been measured in landfill leachate and sewage treatment plant influent and effluent, although secondary treatment has been noted to remove 80-99 percent of Aroclor 1242, and 66 percent of Aroclor 1254 (Feiler 1980). Sample numbers in this study were quite small, however, so removal efficiency is not well documented.

Pavlou and Dexter (1977 in Goldberg 1979) describe a PCB budget for the Sound and mean PCB concentrations for various areas of Puget Sound. Water sediments, suspended matter and biota are given by Pavlou and Horn (1979 in Goldberg 1979). PCB concentrations in water and suspended matter in various regions, and sewage and storm drain concentrations are summarized by Dexter et al. (1981). Specific PCB sources in the Puget Sound area are not well documented. Indirect riverine inputs, rather than marine outfalls, have been estimated to account for the predominant loading, although it is uncertain whether river loadings are due to industrial discharges or to residual chronic input such as spills.

The Duwamish River is recognized to be a large source of PCBs, and high concentrations in water, sediments, and suspended matter may reflect mobilization from original sites. Because of slow degradation and strong adsorption to sediments, assimilative capacity for these compounds may soon be reached in localized areas (Goldberg 1979).

Input by treatment plants has not been well documented. Chapman et al. (1979) indicate PCBs have not been found in Seattle treatment plant effluents or sediments, but the effluent analysis for the Alki treatment plant submitted as part of the 301(h) application indicates PCBs have been observed in minute amounts. Reported effluent levels presented as part of the

301(h) waiver applications for Alki, Carkeek and Redmond plants are identical; it is therefore unclear whether measurements were actually made at Alki. In any case, input from the treatment plants is likely to be small and sporadic.

Disposal of PCB-contaminated dredge spoil is probably a mechanism by which new areas of the Sound are contaminated, and by which additional sediment/water interaction occurs. However, impacts to the water column at the dredging site may be affected by the type of dredge. Observations on use of a pneumatic dredge, which minimizes resuspension of sediment, indicate that no significant quantity of PCBs was dispersed to the water column during dredge operations at a contaminated site (Pavlou et al. 1976). However, other types of dredges would allow greater water column/ sediment interaction to occur, and open water dumping of contaminated dredge spoil would also allow increased water sediment contact.

A 400 g/day PCB loading has been estimated for Puget Sound with the Snohomish, Skagit, and Stillaguamish Rivers (220 g) and Duwamish River (97 g) assumed to provide the bulk of the input (Pavlou et al. 1978 in Dexter et al. 1981).

Trends

Pavlou and Dexter (1979) concluded that a large majority of PCB residues are retained in Puget Sound. Based upon sediment cores, accumulation has been occurring in areas such as Hylebos Waterway for over 20 years, and appears to be continuing. General trends in Elliott Bay sediment cores reflect the historical increase in PCB usage dating from about 1930, but do not as yet show recent decreases, although PCB production was terminated several years ago. However, water column PCB levels have decreased significantly (Dexter et al. 1981). Konasewich et al. (1982) also indicate a rapid decrease in water column levels may be occurring. If this is true, and if PCB movement within the sediments is limited, eventual burial and isolation from the system are likely, although PCB residuals would probably remain in the sediments for some time because of their stability (Dexter et al. 1981).

Information Gaps

There are a number of unknowns concerning PCBs, with many already pointed out by various authors. Major gaps include the following:

- PCB reactions in seawater and PCB release from sediments are unclear. The extent, role, mechanism, and other aspects are not well defined, and there is uncertainty as to whether sedimentation constitutes a temporary storage or a loss to the system. Clarification of these

issues would also allow an evaluation as to the soundness of contaminated dredge sediment disposal in central Commencement Bay.

- PCB metabolites are often more toxic than the parent molecule, but their ecological significance has not been well researched.
- Sources of PCB input to Puget Sound have not been thoroughly identified or quantified, and chemical and physical transport pathways are unclear.
- The biochemical pathways by which PCBs are incorporated into higher trophic levels are not well determined.

Halogenated Aliphatic Hydrocarbons

Twenty-four (formerly 26) halogenated aliphatic compounds are listed as EPA priority pollutants. Callahan et al. (1979) provide detailed descriptions of properties and fates, and give an extensive reference list for each compound. Chapman et al. (1982a) discuss strategies for monitoring these compounds, and discuss their presence in Metro effluent (Chapman et al. 1979). Konasewich et al. (1982) discuss properties, fates, and effects in Puget Sound for the chlorinated butadienes and chlorinated ethylenes, which appear to be the greatest hazards. Information on health effects is given by Sittig (1980).

Properties and Fates

Of the 24 listed compounds, 19 are thought likely to be rapidly lost from the water column by volatilization. Information concerning these compounds is lacking in many respects, but adsorption to particulates is generally considered unimportant, and biodegradation slow and insignificant. For a few compounds such as chloroethane, bromomethane, and the dichloropropanes, hydrolysis may be an important fate process along with volatilization. A few compounds such as tri- and tetrachlorethene, tetra- and hexachloroethane, and dichloropropane and dichloropropene also have a high enough log octanol/water partition coefficient to indicate that bioaccumulation may occur, although in many cases data are lacking.

The five remaining aliphatic compounds are somewhat different. The fate of three (bromodichloromethane, dibromochloromethane, and tribromomethane) is unknown. The last two are hexachlorobutadiene and hexachlorocyclopentadiene. Both appear to pose a greater aquatic hazard than the other halogenated aliphatics because they tend to bioaccumulate and adsorb to sediments more easily.

Hexachlorobutadiene is very persistent. Adsorption is an important transport process, and bioaccumulation and volatilization may also occur. No evidence has been found for biomagnification, and no information has been found on biodegradation.

Hexachlorocyclopentadiene has several significant fate and transport processes, depending upon the aquatic system. Near-surface photolysis appears to be the prominant transport process in lakes, while volatilization and hydrolysis appear to be more important transport processes in turbid rivers. Adsorption to particulates is also a lesser fate process. However, data are insufficient to determine a single predominant fate process (Callahan et al. 1979). Bioaccumulation by both plants and animals has been shown, and may be significant for some systems. Biotransformation/biodegradation does not appear to be an important process.

Sources and Distribution

Many of the halogenated aliphatics do not appear to be a problem because they volatilize so rapidly. Only two groups of compounds within the halogenated aliphatics are considered to be contaminants of concern by Konasewich et al. (1982): chlorinated butadienes and chlorinated ethylenes (ethenes).

Chlorinated butadienes (CBDs) are formed as by-products in a variety of industries including the manufacture of hexachlorobenzene, tri- and tetrachloroethylene, tetrachloromethane, and pesticides (Sittig 1980). Sources of chlorinated ethylenes include textile mills, iron and steel manufacturing, paint and ink formulators, carwashes, and dry cleaners (Metro 1980; Sittig 1980). Some halogenated aliphatics (chloroform, dichlorobromomethane, dibromochloromethane, and tribromomethane) can also be formed from organic compounds when exposed to chlorination in municipal drinking water or wastewater facilities. Chloroethane and ethers can also be converted to more highly chlorinated compounds (Callahan et al. 1979).

Several types of CBDs have been found in water, sediments and/or biota in most major areas of Puget Sound. Konasewich et al. (1982) summarize levels in sediments for major areas and in biota of Hylebos Waterway. Riley et al. (1981) also discuss CBDs in waterways adjacent to Commencement Bay, and suggest that levels in water indicate continuing impact. Malins et al. (1982) list levels in Puget Sound in relation to biological abnormalities.

Highest levels of chlorinated ethylenes were noted in Hylebos Waterway. As these compounds are quite volatile, the concentrations observed imply considerable discharge (Konasewich et al. 1982).

Eleven of the 26 halogenated aliphatics have been observed in West Point effluent. However, as effluent is sampled prior to chlorination, it is possible that additional compounds may be produced during chlorination and be present in the finished effluent.

Information Gaps

- There appears to be ongoing input, but sources of CBDs and chlorinated ethylenes are not identified.
- Concentrations in water and sediment are not well documented. Uptake mechanisms and ability of biota to concentrate these chlorinated ethylene compounds in Puget Sound are also uncertain. Information on chlorinated butadienes is similarly lacking.
- Understanding of the above would allow evaluation of the impact caused by disposal of contaminated dredge spoil to other areas of Puget Sound.
- Effect of chlorination on production of these compounds in Metro effluent has not been determined.

Halogenated Ethers

Six (previously seven) ethers are listed as priority pollutants by EPA. Callahan et al. (1979) summarize known information concerning their physical properties and probable fates, and give an extensive reference list for these compounds. Recommendations concerning monitoring of these compounds are given in Chapman et al. (1982a), and their presence or absence in Metro effluent is discussed by Chapman et al. (1979). Information on health effects is given by Sittig (1980).

Properties and Fates

The aquatic fate of the ethers is quite variable. Two compounds, (4-chlorophenyl phenyl ether and 4-bromophenyl phenyl ether), behave somewhat differently from the others. Little information is available for either compound, but photolysis near the water surface may be a potential fate process for both. Significance of volatilization cannot yet be assessed, but hydrolysis and oxidation are not considered significant processes. Adsorption is believed to be a likely process for both because of high affinity for lipophilic organic materials relative to water, and there is evidence of adsorption by organic materials. Adsorption by clays is probable. Bioaccumulation has been demonstrated for chlorophenyl and is likely for bromophenyl. Both are rapidly degraded by activated sewage sludge, but data indicate potential persistence in natural surface waters (Callahan et al. 1979).

The remaining four ethers [bis(2-chloroethyl) ether, bis(2-chloroisopropyl) ether, 2-chloroethyl vinyl ether, and bis(2-chloroethoxy) methane], appear to remain primarily in the water column. Direct photolysis is probably unimportant. Bioaccumulation is probably unimportant because of their low partition coefficients (Chapman et al. 1982a), although data are limited. Biotransformation in natural systems is probably not important, although detailed information is lacking. Rapid

hydrolysis is the most important fate for bis(chloromethyl) ether and may be the only degradative process that operates for bis(2-chloromethoxy) methane. This process is slow but may be important for the others as well. Volatilization is likely an important path from water to atmosphere for 2-chlorethyl vinyl ether as well. Adsorption does not appear an important transport process for any of them, although some may adsorb slightly to clays or humic materials (Callahan et al. 1979).

Sources and Distribution

Halogenated ethers are used as solvents for fats, waxes and greases, and may be found in paint removers, cleaning products, or as contaminants in other solvents. Some are used in the textile industry as cleaning and wetting agents as well (Sittig 1980; Metro 1980).

Little information on these compounds in Puget Sound is available. Konasewich et al. (1982) indicate bis(2-chloroisopropyl) ether, 4-bromophenyl phenyl, and bis(2-chloroisopropyl) ether have been observed in Puget Sound sediments in the Metro area in low concentrations. They classify them as category 4 compounds (toxic contaminants in localized areas for which source identification is necessary). They have not been noted in Metro effluent although three of them [bis(2-chloroisopropyl) ether, bis(2-chloroethyl) ether, and bis(2-chloroethoxy) methane] were observed in West Point sediments. It is possible they are formed as part of the chlorination process (Chapman et al. 1979).

Information Gaps

- Levels of these materials in the water column in the vicinity of the contaminated sediments are apparently not documented, and sources are unknown.

Monocyclic Aromatic Hydrocarbons

There are 23 monocyclic aromatic compounds on the EPA priority pollutant list. These include benzenes, toluenes, phenols, and cresols. Callahan et al. (1979) provide detailed information on properties and aquatic fates, and an extensive reference list for each compound. Chapman et al. (1979, 1982a) discuss strategies for monitoring these compounds and discuss their presence in Metro effluent. Konasewich et al. (1982) review fate data for the chlorinated benzenes, evaluate their presence in Puget Sound, and recommend research needs. Synergistic effects between metals and various hydrocarbons are discussed in Gruger et al. (1981), and information on health effects is given by Sittig (1980).

Properties and Fates

Benzenes and Toluenes. Nine benzene and three toluene compounds are included in the EPA listing. All can accumulate in sediments, and all of the chlorinated benzenes can bioaccumulate as well. The presence of chlorine has been shown to make compounds more resistant to degradation. Chlorinated benzenes (chlorobenzene, di-, tri-, and hexachlorobenzene) are all very persistent, with high affinity for lipids, and low solubility in water. Volatilization, bioaccumulation, and adsorption are all competing fates, (except for hexachlorobenzene, which volatilizes slowly). The rate at which each occurs dictates which process will predominate. The chlorinated benzenes biodegrade slowly, if at all. Bioaccumulation of hexachlorobenzene is primarily from aqueous uptake, not diet, and depuration is more rapid than for some other persistent compounds such as DDT. Biomagnification probably does not occur.

The nonchlorinated benzenes (benzene, ethylbenzene, and nitrobenzene) react somewhat differently. Adsorption is considered probably significant for all of them. They have little potential for bioaccumulation, and have some minor ability to degrade. The predominant fate process for benzene and ethylbenzene is volatilization, although benzene's solubility indicates some will persist in the water column. Photolysis and biodegradation are the most important fate processes for nitrobenzene, but both processes may lead to production of benzidine and diphenylhydrazine, priority pollutants themselves (Callahan et al. 1979).

The toluene compounds (toluene, 2,4-dinitrotoluene and 2,6-dinitrotoluene) all have little potential for bioaccumulation. The primary aquatic fate for toluene is volatilization, although adsorption to suspended sediment has some undefined role. The relative importance of biodegradation for toluene is also undetermined.

The major fates for 2,4-dinitrotoluene are photodestruction, oxidation, and biodegradation, although it is unclear which is predominant. Biodegradation is likely to be slow. Sediment adsorption for these two compounds is a major transport process, and may also provide reaction sites for destruction. Persistence of these compounds is uncertain.

Phenols and Cresols. Nine phenol and two cresol compounds are included on the EPA list. Fates of phenol include photooxidation, metal-catalyzed oxidation, and biodegradation by microorganisms, the dominant pathway depending on environmental conditions. Some volatilization occurs, but adsorption and bioaccumulation are not important processes.

Because they are chlorinated, the chlorophenols are more resistant to biodegradation than phenol, but photolysis and microbial degradation are probably the major fate processes. They do not significantly bioaccumulate, with the important exception of pentachlorophenol. One of its degradation products, pentachloroanisole, has an even greater tendency for bioaccumulation than the parent compound itself. Volatilization is not important for this group. Adsorption is important primarily for pentachlorophenol, which is adsorbed to organic materials in sediments.

Nitrophenols (2- and 4-nitrophenol, and 2,4-dinitrophenol) tend to be persistent in aquatic environments, and to inhibit microbial growth by disrupting metabolic processes through uncoupling oxidative phosphorylations. In general they do not volatilize or bioaccumulate, but they do adsorb strongly to clays. Slow photolysis may be the main degradation process. Data for 2,4-dimethylphenol is conflicting, but adsorption to clay seems unlikely and bioaccumulation and volatilization appear probably unimportant. Some adsorption by lipophilic materials may occur. Photooxidation and metal-catalyzed oxidation may be important in aerated surface waters.

The cresols' most probable fate is photolysis. Both p-chloro-m-cresol and 4,6-dinitro-p-cresol should show a tendency to bioaccumulate, but toxicity would probably prevent it. Biodegradation is uncertain. The latter cresol should show a strong adsorption to clays (Callahan et al. 1979).

Sources and Distribution

Benzene is produced primarily from coal tar distillation and is used extensively throughout the chemical industry. The chlorinated benzenes are used in chemical synthesis, herbicides, dye manufacturing, wood preservatives and other industries. Toluenes may be converted to benzene, used in chemical production as solvents or in manufacture of explosives, dyes, and urethene polymers.

Phenols and cresols have many industrial and medical uses including manufacture of pesticides, herbicides, fungicides, preservatives, and antiseptics (Sittig 1980). The chlorophenols may also be inadvertently produced by chlorine reactions during wastewater disinfection or drinking water treatment.

Chlorination of municipal effluent may also result in formation of monocyclic aromatic compounds including the priority pollutants chlorobenzene and 1,3-dichlorobenzene. These may form during Metro wastewater treatment, but as sampling previously was done prior to chlorination, their formation has not been determined (Callahan et al. 1979). The Metro Toxicant Pretreatment Planning Study (TPPS) report may provide more appropriate data on the effects of chlorination on effluent.

Malins et al. (1982a) discuss abnormalities in biota and concentrations of aromatic hydrocarbons in sediment and biota for the major areas of Puget Sound. Highest concentrations were observed in Elliott and Commencement Bays, with more than 500 aromatic compounds observed in the Hylebos Waterway sediments.

Dexter et al. (1981) discuss distribution, concentration and sources of aromatic hydrocarbons, but cover primarily the polycyclic hydrocarbons.

Chapman et al. (1979) identify six monocyclic aromatics (primarily the chlorinated compounds) in West Point effluent and one in West Point sediments. They classify the dichlorobenzenes, pentachlorophenol and 2,4-dimethylphenol as being most important (class 1 pollutants), and recommend determining concentrations in both sediment and biota in outfall areas. Pentachlorophenol is one of the four compounds Chapman et al. (1979) consider as being of special significance because of its high toxicity, wide use, demonstrated presence in effluent, and ability to accumulate in sediments and biota.

Konasewich et al. (1982) review data on the levels of hexachlorobenzene found in Puget Sound, discuss significance to Puget Sound, and compare levels with those reported in the literature. They note all priority pollutant benzenes and toluenes were observed in sediments or biota, but not phenols and cresols. They consider benzene, trichlorobenzene, ethyl- and nitrobenzene and toluene as class 6 contaminants (of no immediate concern based on existing knowledge); the dichlorobenzenes and chlorobenzene as class 4 and 5 contaminants (toxic, but for which additional information on distribution, form, concentration, and source identification is required); the dinitrotoluenes as class 2 contaminants (those for which an ecological hazard evaluation could not be provided); and hexachlorobenzene as a class 1 contaminant (critical and of concern). Konasewich et al. (1982) consider chlorinated benzenes to be contaminants of concern, based on their toxicity and level of distribution in Puget Sound biota and sediments.

Information Gaps

- Sources of high concentrations, especially of chlorinated benzenes, are not identified.
- It is unclear to what extent high concentration in sediments contributes to or affects uptake by biota.
- The role of sediment in concentrating organic contaminants in the Sound is not well understood.
- Measurements of these priority pollutants in effluents appear to have been made only infrequently, and may not be totally representative.

- The effect of chlorination on municipal treatment plant effluent, and the possible formation of new chlorinated compounds, has not been determined. Some data may be made available by the Metro TPPS report if appropriate sampling techniques were used.

Phthalate Esters

There are six phthalate esters listed as priority pollutants by EPA. Callahan et al. (1979) describe their physical properties and probable fates, and provide an extensive reference list. Chapman et al. (1982a) recommend strategies concerning monitoring of these compounds. Presence of esters in Metro effluent is also discussed by Chapman et al. (1979). Fates, sources, significance to Puget Sound, and research needs are discussed by Konasewich et al. (1982). Information on health effects is given by Sittig (1980).

Properties and Fates

Bis(2-ethylhexyl) phthalate is the most studied of the phthalate esters; others are much less known, and their properties are somewhat inferred from those of the group as a whole. In natural waters, volatilization, oxidation, hydrolysis, and photolysis are not expected to be significant fate processes. Aquatic transport mechanisms are thought to be primarily adsorption onto suspended matter and biota, and formation of complexes with natural organic substances. Bioaccumulation, biotransformation, and biodegradation are all considered important fate processes but the degree to which these dominate is not clear. The compounds are lipophilic and are likely to be adsorbed by both uni- and multicellular animals and plants. There is evidence of biodegradation and metabolism at varying rates by microorganisms and higher animals, depending on environmental conditions. Esters are not likely to biomagnify (Callahan et al. 1979).

Model simulations indicate concentrations of short-chain alkyl group esters (dimethyl, diethyl, and dibutyl phthalates) in the ecosystem can be expected to approach a steady state if ecosystem input is constant; chemical and biochemical transformations compete favorably. Longer chain esters tend to have slow transformation processes, and transport processes by adsorption will predominate. However, phthalate esters appear more readily degradable than other persistent compounds such as PCBs and DDT (Callahan et al. 1979).

Sources and Distribution

Phthalate esters are primarily used as plasticizers in production of polyvinyl chloride, but are also used as defoaming

agents in paper production, in lubricating oils, cosmetic products and other industries (Sittig 1980).

Few studies involving esters have been made. Five different esters have been observed within Elliott Bay sediments during studies by Metro in 1979 (Konasewich et al. 1982), with diethylhexyl phthalate being most predominant. Four of the esters have been shown to exist in Metro effluent and the other two have been found in nearby sediments. Chapman et al. (1979) recommend monitoring of these compounds in both sediment and biota. Phthalate esters are classified as being category 1 (contaminants of concern) by Konasewich et al. (1982), based on their wide distribution and the possibility of chronic effects at low levels.

Information Gaps

- Levels of phthalate esters in biota and sediments of Puget Sound have not been determined for most areas. Tacoma is a likely area to expect their occurrence. Metro's TPPS report may provide some data for the Central Basin.

Polycyclic Aromatic Hydrocarbons

Sixteen polycyclic aromatic hydrocarbons (PAHs) are listed as EPA priority pollutants. Callahan et al. (1979) provide detailed information on properties and aquatic fates and give an extensive reference list for each compound. Chapman et al. (1979, 1982a) discuss monitoring strategies for these compounds and their presence in Metro effluent. Malins et al. (1982a) and, to a lesser degree, Dexter et al. (1981) summarize knowledge of these compounds in the Puget Sound water, sediments and suspended particulates. Riley et al. (1981) give detailed information on Blair and Hylebos Waterways of Commencement Bay. Konasewich et al. (1982) review fates, sources and significance to Puget Sound for selected PAHs, including information on PAHs not listed by EPA as a priority pollutant, but believed to be of significance (chlorinated and bromo-naphthalenes, and other halogenated PAHs). These have received less attention than those listed, and little data on their distribution, or concentrations are available at present.

Properties and Fates

Two- and Three-ring Compounds. Very little is known concerning the two-ring compounds (acenaphthene, acenaphthylene, fluorene and naphthylene) or the three-ring compounds (anthracene, fluoranthene and phenanthrene). Data suggest they will adsorb strongly to particulates (especially organics) and biota. Volatilization is unlikely to be as important a transport

process as adsorption for any but napthalene, where it may be more important, and anthracene, where these processes may compete. Bioaccumulation for compounds of four rings or less is short term and often not significant because they are easily metabolized. Biodegradation is considered the ultimate fate process (Callahan et al. 1979).

Four-ring Compounds. With the exception of benzo[a]anthracene, properties and fates are not well researched for the four-ring aromatic compounds (benzo[a]anthracene, benzo[b]fluoranthene, benzo[k]fluoranthene, chrysene, and pyrene). It is likely that these compounds will accumulate in sediments and biota because they tend to adsorb to suspended particulates, especially those high in organic matter. This is probably the dominant transport process. A small amount may dissolve and be degraded to some extent by photolysis and oxidation. In general, volatilization does not appear important, and hydrolysis is unlikely. Ultimate fate of this group appears to be biodegradation and biotransformation. Many diverse species including microorganisms, benthic organisms and vertebrates can metabolize these; biodegradation may be the ultimate fate process (Callahan et al. 1979).

Five- and Six-ring Compounds. Few data specific to five- and six-ring compounds (benzo[ghi]perylene, benzo[a]pyrene, dibenzo[a,h]anthracene, and indeno[1,2,3,-cd]pyrene) are available except for benzo[a]pyrene. The compounds are relatively insoluble in water, but will adsorb onto particulates and biota, and this appears to be the most important transport process. Although compounds with four or more rings are more slowly metabolized than those with fewer rings, bioaccumulation is fairly short term. Compounds having four or more rings are also degraded more slowly by microorganisms, benthic organisms, and vertebrates, but it is probably the ultimate fate process. Biodegradation may be much more rapid (and therefore more important) in those aquatic areas which are chronically contaminated by polycyclic aromatic hydrocarbons (Callahan et al. 1979).

Sources and Distribution

Polycyclic aromatic hydrocarbons can be formed through hydrocarbon combustion, or released during oil spills. The major sources include heat and power generation and refuse-burning facilities. PAHs are also used in formulation of dyes, solvents, lubricants, and motor oils. Smaller ringed compounds have fewer uses than the larger-ringed ones (Sittig 1980). Chlorinated napthylenes also may be produced by chlorinated wastewater treatment plant effluents (Konasewich et al. 1982).

Low levels of PAHs in sediments and the biota have been identified in all areas of Puget Sound and the Strait of Juan de Fuca (Dexter et al. 1981). Concentrations in biota tended to be

highest in Hylebos Waterway, Commencement Bay and the Duwamish River, while Elliott Bay, West Point, Duwamish River, Hylebos Waterway, and Sinclair Inlet had highest sediment concentrations. Malins et al. (1982a) summarize concentration of aromatic hydrocarbons in sediments and biota and discuss abnormalities of organisms living within contaminated areas.

Nearly all priority polycyclic aromatics have been observed in Metro effluent except for acenaphthene. These compounds are classified by Chapman et al. (1979) as class 1 compounds (those of most concern). In addition, they consider benzo[a]pyrene to be one of four compounds of special significance because of its high levels, demonstrated presence in effluent, ability to accumulate in sediments and biota, and potential links to hepatomas in bottomfish.

Konasewich et al. (1982) indicated all of the priority pollutant PAHs have been observed in Puget Sound sediment, biota, suspended particulates, or a combination of these. They classify napthalene, anthracene, fluoranthene, benzo[a]anthracene, benzo[k]fluoranthene, benzo[a]pyrene, and dibenzo[a,h]-anthracene as being category 1 compounds (contaminants of concern). The remaining PAHs are considered to be category 2 compounds (contaminants of possible concern but difficult to evaluate). They also consider chlorinated and bromonaphthalenes and other halogenated PAHs to be contaminants of concern.

Fluoranthenes appear to be the most prominent PAHs in terms of concentration, although levels in biota are normally low. Naphthalenes are found in high concentrations in Elliott and Commencement Bays, and input appears ongoing. Their metabolites are extremely toxic but not well known. Compared to the literature for other areas, benzoanthracenes appear to be at quite high concentrations in Puget Sound.

A number of PAHs not on the priority pollutant list are potentially of concern. Low levels of chlorinated and bromonaphthylenes have been shown to cause sublethal effects in organisms, and their similarity to PCBs and naphthylene (priority pollutants) indicates they may be of potential hazard. Their metabolites are also of possible concern (Konasewich et al. 1982). Other halogenated PAHs may pose similar problems. Many of these compounds have been observed in Puget Sound and concentrations are documented by Malins et al. (1982a), Konasewich et al. (1982), and Riley et al. (1981). Curl (1982) has constructed a preliminary budget for PAH mass loading in the Central Basin, indicating riverine and municipal discharge each contribute approximately 200 kg/yr, while atmospheric input is estimated at 300 kg/yr.

Information Gaps

- Levels of concentration in edible biota are not well known for many PAHs.
- Information concerning chlorinated and bromonaphthylenes, their metabolites, and other halogenated PAHs not on the EPA listing is poorly documented, and their concentrations, toxicity, degradation rates and sources are not well known.
- Sources for most PAHs are not identified.

Nitrosamines and Miscellaneous Compounds

There are three nitrosamine and four miscellaneous compounds on the EPA priority pollutant list. Information concerning properties and probable fates is given in Callahan et al. (1982a). Sittig (1980) discusses health aspects of these compounds. Chapman et al. (1979) discuss their presence in Metro effluent, but apparently little other local information is available. Benzidine and diphenylhydrazine may be produced in the environment by photolysis or biodegradation of nitrobenzene, a monocyclic aromatic listed as a priority pollutant.

Properties and Fates

Property and fate information below is taken from Callahan et al. (1979). Slow photolysis is probably the major fate process for dimethyl nitrosamine and di-n-propyl nitrosamine. Bioaccumulation, volatilization and adsorption are insignificant, and little oxidation hydrolysis or biodegradation occurs.

Diphenyl nitrosamine may bioaccumulate, and both adsorption and photolysis may be important, although information on the fate processes is limited.

Benzidine is rapidly adsorbed by clay. Although adsorption is considered the major fate, some photolysis probably occurs. It can be rapidly oxidized by other cations but is not easily degraded and is not bioaccumulated.

The main fate of dichlorobenzidine is probably adsorption to particulates, although photolytic dechlorination occurs in shallow water. It has also been shown to bioaccumulate in fish at subtoxic levels. No biodegradation occurs.

Diphenylhydrazine has the potential for bioaccumulation, but there is no evidence that this has occurred. The main transport and fate mechanism is probably adsorption to sediments. Some photolysis to aniline occurs; it is slow, but may be important in the final destruction of the compound.

Volatilization is probably the major transport process for acrilonitrile. Adsorption and bioaccumulation are not likely to occur, and hydrolysis is not considered significant.

Sources and Distribution

Nitrosamines are naturally widespread, and anthropogenic sources are negligible. Synthetic production is small, but they are used in rubber processing and pesticide manufacture (Sittig 1980).

Diphenylhydrazine is used primarily in dye manufacturing of benzidine. Dichlorobenzines have been detected in finished drinking water, and acrilonitrile is used primarily in production of polymers (Sittig 1980).

Few local data are available on these compounds, and none appears to have been observed in local sediments, waters or biota. None has been observed in Metro effluent (Chapman et al. 1979).

Information Gaps

- Transport, fate, and bioaccumulation/biotransformation potential of many of these compounds are not well understood or documented.

Polychlorinated Dibenzofurans

Polychlorinated dibenzofurans (PCDFs) are formed as by-products in the manufacture or disposal of PCBs or polychlorinated phenols. Structurally they resemble chlorinated dibenzodioxins and TCDDs, which are among the most toxic chemicals known. There are 135 possible isomers, and changes in position of one chlorine atom may significantly alter toxicity. Determination of the actual structure of Puget Sound compounds is therefore important. Little research has been done locally on these compounds.

Information below is primarily summarized from Konasewich et al. (1982), who provide a review of toxicity and fate data, sources, and research needs. Much of the information is based on known behavior of similar compounds.

Properties and Fates

Sedimentation is likely to be one of the most significant fate processes for PCDFs, as their lipophilic nature indicates potentially high adsorption to organic-containing sediments. Based upon their similarity to other compounds, they are probably not biologically degraded in the environment, and hydrolysis, photolysis, and volatilization would likely be minimal. Potential for biological uptake is high, although there are indications that higher organisms can rapidly depurate PCDFs.

Sources and Distribution

PCDFs exist as impurities in PCBs and chlorinated phenols. They also are found in coal tar coatings of public water systems, in flue gasses and fly ash from incineration and heating facilities, and as by-products of coal conversion or burning of PCBs or pentachlorophenol (PCP). PCP is manufactured in Tacoma, and is widely used in the lumber industry in pulpmills, sawmills, and lumber terminals.

Hexa-, penta-, and tetrachlorodibenzofurans have been detected in central Puget Sound sediments by Malins (in Konasewich et al. 1982), although levels were not quantified and possible effects can only be speculated on. A later analysis of Tacoma sediments by Malins et al. (1982a) also indicated presence of low level dichlorodibenzofurans.

Konasewich et al. (1982) consider PCDFs to be category 1 compounds (contaminants of greatest concern) because high levels of PCBs in Puget Sound sediments and extensive usage of PCP suggests they may be widespread, and they are highly toxic to birds and mammals. Toxicity to aquatic organisms is not well known.

Information Gaps

- There are many potential PCDF sources, but information is lacking concerning distribution, degree of contamination, and the isomers involved.
- Should widespread contamination be found, sources, toxicity to biota (especially benthic organisms), bioaccumulation and uptake information would be desirable.

Petroleum Hydrocarbons

Aromatic hydrocarbons have been dealt with previously in this chapter. Crude oil and fuel oils are considered in this section as distinct petroleum products because of concern over potential oil spills, especially within northern Puget Sound. Increases in tanker transport will increase the spill risks.

Properties and Fates

Fractionation of oil occurs upon contact with water; portions of the oil dissolve while others adsorb to particulate matter or evaporate. The more water-soluble aromatic hydrocarbon fraction is responsible for acute toxicity, but fractions adsorbed in particulates and accumulated in sediments may possibly interrupt biological functions such as chemotaxis (Blumer et al. 1973). The water-soluble fractions are also

considered good tracers for pollution studies because of their mobility and relatively slow biodegradation (Zürcher and Thuer 1978). Degradation studies by Westlake et al. (1978) estimate approximately one-third of Prudhoe Bay crude oil (by weight) is lost due to mineralization by microorganisms, approximately one-third was lost due to physical/chemical weathering, and approximately one-third remains as residue. Zürcher and Thuer (1978) studied the weathering processes of fuel oil and found that important primary initial processes include fast dissolution, adsorption, and agglomeration, followed by sedimentation and biochemical alteration. Turbulence and suspended solids levels also affect the process.

Dissolution of the one- and two-ring hydrocarbons occurs independently of the oil type (fuel oil, gasoline, or crude oil) and reaches a saturation level that depends largely on aromatic hydrocarbon content (Zürcher and Thüer 1978).

Interactions between oil and particulates include adsorption of higher boiling hydrocarbons (molecular weight >250) to particulates, and agglomeration. The former depends upon character of the particulate surface, and the latter upon formation of dispersed oil droplets. Agglomeration has a substantial role in sedimentation of oil as well (Zürcher and Thüer 1978).

Studies by Westlake and Cook (1980) and Westlake et al. (1978) on oil degradation processes in Puget Sound water and sediment showed microbial degradation ability to be greatest in areas adjacent to refineries and in areas of high commercial activity. They also suggest bacteria, not yeasts or fungi, are the most active group in degrading oil in the environment. Nitrogen and phosphorus levels are also primary factors in controlling microbial activity, and enrichment with nutrients produced greater degradation. Degradation was also found to be greater in summer than winter in both beach sediment and the water column.

Various oil fractions were removed differently from the environment; removal of compounds in the saturate fraction was slow, followed by an extended period of high removal rate, while aromatics were continually removed at a low rate, followed by a short period of rapid loss. Vanderhorst et al. (1980a, 1980b) monitored oil retention and recovery rates for various substrates in the Strait of Juan de Fuca following an experimental spill. The data indicated that total hydrocarbon concentration decreased by 85 percent and 97 percent, respectively, for fine and coarse sediment within 15 months, which suggested that total hydrocarbons would reach background levels in approximately 18.5 months. Because spills represent an unavoidable and potentially acute situation, these recovery studies may be of interest primarily in contingency planning.

Methodology for detection and measurement of hydrocarbons in Puget Sound sediments and molluscs is given by MacLeod et al. (1977). They also present recommendations for use in the development of a hydrocarbon baseline investigation program for northern Puget Sound and the Strait of Juan de Fuca. Their results ranked oil retention from highest to lowest for commercial clam beds, sand, and concrete brick (representing rock habitat), respectively. Substrate higher in the intertidal zone also retained oil longer. Sand and sandy mud substrate lost saturate compounds at the same rate as total oil. Aromatic compounds were lost much more quickly in sand substrate, while in the clam bed habitat (sandy mud) they did not change from initial concentrations in 3 months.

A 2-year baseline study by Brown et al. (1981) on hydrocarbon concentrations in sediment and mussels indicated sediments took up hydrocarbons more slowly, and retained them for over a month. Nearby mussels absorbed them more readily, but also returned to normal levels more quickly.

Sources and Distribution

Sources of petroleum hydrocarbons include chronic nonpoint sources such as recreational boating, industrial discharges, stormwater runoff, and river input, as well as acute and potentially larger inputs such as unintentional spills. Calculations of actual Puget Sound loadings for grease and oil are discussed in Chapter 4 and in Appendix D. Pollution caused by petroleum hydrocarbons can be minimized, but the amount and distribution can never be totally predicted from year to year because of unexpected spills of unpredictable quantity.

Information Gaps

- Existing levels of petroleum hydrocarbons in sediment and biota are not well documented.
- The effect of hydrocarbons absorbed to sediments on benthic and demersal species is not well quantified.

Metals and Inorganics

Heavy metals are generally considered to be pollutants of environmental concern because of their toxicity and tendency to accumulate in sediments and biota. The biological effects of metals in the marine environment are influenced by their oxidation states and the types of organic and inorganic compounds they are associated with. The pH, concentration of other chemicals, and ability of the metal to be reduced or oxidized also affect its toxicity.

Fifteen metals and inorganics have been incorporated into the EPA priority pollutant listing. Twelve of the 15 adsorb to sediments and bioaccumulate (although bioaccumulation tends to be more important for arsenic, cadmium, chromium, copper, lead, mercury, and zinc, than for nickel, beryllium, selenium, silver and thallium). The other three substances (cyanide, asbestos, and antimony) react somewhat differently.

Because metals have been extensively sampled relative to other compounds, each will be discussed separately. Callahan et al. (1979) and Konasewich et al. (1982) provide detailed data on structure, fates and processes. Dexter et al. (1981) summarize information on Puget Sound, and Chapman et al. (1979) provide information on Metro effluent characteristics. Property and fate information for metals summarized below is primarily from Callahan et al. (1979) and Konasewich et al. (1982). Sittig (1980) provides information on health effects, and Gruger et al. (1981) discuss synergistic effects between metals and various hydrocarbons.

Arsenic

Properties and Fates. Arsenic exists in four oxidation states, each having different properties. It is quite mobile, and cycles through water, sediment and biota. Photolysis is not considered an important fate process. Volatilization is considered unimportant by Callahan et al. (1979) except in extreme reducing environments, where anaerobic bacteria can reduce arsenic compounds to dimethyl and trimethyl arsene, which are extremely toxic and volatile. Konasewich et al. (1982) believe volatilization may be of significance to the fate of arsenic in Puget Sound. In most cases sediments and ocean water are the primary sinks for arsenic, but metabolism to organic arsenicals by bacteria and benthic organisms recycles much of it.

Bioaccumulation occurs, but is most significant at lower trophic levels. Fish may accumulate arsenic through both water and food, but uptake from the water column appears to be more important (Konasewich et al. 1982). Reported concentrations in organisms are generally low, because high toxicity prevents great accumulation.

Adsorption-desorption to and from particulates does not appear significant in estuarine or marine environments (Konasewich et al. 1982). Crecelius (pers. comm.) estimated an arsenic budget for Puget Sound; the estimated budget indicates that discharge to the Strait of Juan de Fuca is the major sink, with the remainder primarily deposited in the sediments.

Arsenic is considered to be either a carcinogen or cocarcinogen, with a latent period of 20-30 years. It is considered by Dexter et al. (1981) to be one of the metals having greatest potential for toxicity to organisms, and Konasewich et al. (1982) have identified it as a contaminant of concern for Puget

Sound. Crecelius (pers. comm.) does not consider arsenic to be of concern because there is no evidence that it is elevated in the tissues of biota, contribution by man is relatively small, and seawater already has a relatively high concentration.

Sources and Distribution. Sources are both natural and anthropogenic. Arsenic is present in soils, but is also formed as a by-product of ore smelting, and is used in herbicides, preservatives, drugs, ceramics and glass, and a number of other industries (Sittig 1980; Metro 1980).

The northern rivers which enter Puget Sound (Skagit, Snohomish, Stillaguamish and Duwamish) have arsenic concentrations approximately six times those of the more southern rivers, which primarily reflects the mineralogic differences of the drainage basins (Dexter et al. 1981). Shoreline erosion and advection (transport of water through Admiralty Inlet) are sources, as are municipal treatment plant effluent and atmospheric input. Estimated input for municipal and industrial discharges, riverine sources, erosion, and advection are given by Dexter et al. (1981) and by Crecelius (pers. comm.). In both cases natural sources are estimated to be greatly predominant. Although relative contribution from anthropogenic sources seems minor, some regional areas are heavily impacted, and arsenic is considered to be one of the metals having greatest potential for producing toxic response in organisms and their consumers (Dexter et al. 1981).

Arsenic measurements for all major areas of Puget Sound sediments are summarized by Dexter et al. (1981). It has been found in high concentrations in sediments of all four urban embayments (Elliott and Commencement Bays, and Budd and Sinclair Inlets). In Tacoma, liquid and slag discharges from the ASARCO smelter, storm drains, and sewer overflows have produced very high concentrations of arsenic (and antimony) along the western bay, but atmospheric emissions are also a likely source. Northwesterly flow along the southwest shore of Commencement Bay minimizes impact there, but sediments in Quartermaster Harbor and to the south of Fox Island have significantly higher arsenic levels than other areas. Deep sediments in East Passage also have elevated levels (Dexter et al. 1981). Measurements in the water column indicate arsenic associated with particulates is minor in comparison to the concentration of dissolved material (Konasewich et al. 1982).

Information Gaps.

- Speciation of arsenic and the significance of volatilization as a fate process in Puget Sound are not well understood.

Cadmium

Properties and Fates. Cadmium is relatively mobile because it dissolves readily in water. As such, it may pose a hazard to all forms of aquatic biota. Adsorption to suspended matter reduces concentrations in the water column. In polluted or organic-rich areas, cadmium adsorption to organic matter is considered the most important fate process. In unpolluted areas, adsorption to clay, hydrous iron and manganese is the most important (Callahan et al. 1979). There is also a tendency for it to be associated with fine grained sediment and high organic carbon levels (Malins 1980 in Konasewich et al. 1982).

Bioaccumulation is considered an important fate process. Cadmium is strongly bioaccumulated at all trophic levels, and uptake increases with increased temperature and decreased salinity. It can be accumulated to much higher levels than water concentrations, although usually to a level lower than that of the sediments. It is not known to be methylated.

The form of cadmium within the sediments is dependent on redox conditions. In oxidizing conditions, carbonate formation is the controlling process and soluble chlorides are the major complexes. In reducing conditions, the formation of generally insoluble sulphides regulates the amount of dissolved cadmium available.

When river particulates enter an estuary, cadmium is probably released to the water. The release of cadmium from Puget Sound sediments appears to occur readily, and may be of importance to health of the biota (Konasewich et al. 1982). Photolysis and volatilization are not considered important fates.

Sources and Distribution. Cadmium is used industrially in plating, and in manufacture of paint, varnish, batteries, plastics, fungicides, fertilizers, rubber tires, and motor oil (Sittig 1980; Konasewich et al. 1982). It can also be released to the atmosphere in smelting of zinc, copper, and lead ores. Crecelius (pers. comm.) has estimated an annual input of approximately 44 tons to the Sound, the majority contributed through advection, with riverine, sewage and atmospheric input considered of less importance.

Crecelius (pers. comm.) does not consider cadmium to be a metal of concern, because there is no evidence of elevation in tissues of biota, and contribution by man is minor compared to that of advection. On the other hand, Konasewich et al. (1982) consider it as a contaminant of concern because sediment levels are highly elevated compared to regulatory criteria for classifying sediments. Cadmium is one of the four compounds on the priority pollutant listing singled out by Chapman et al. (1979) as being of special significance because of its high toxicity, demonstrated presence in effluent, and ability to accumulate in sediments and biota.

Concentrations of cadmium for various areas of Puget Sound sediment are given in Malins et al. (1981). Effects of levels found in Puget Sound are discussed in Konasewich et al. (1982). Dexter et al. (1981) do not discuss it in detail, because data were considered limited and of unknown quality, and regional impacts were considered to be minor.

Information Gaps.

- o Sources of cadmium are not well identified.
- o There appear to be some differences of opinion as to quality of existing data on cadmium.

Chromium

Properties and Fates. Chromium exists in two oxidation states: hexavalent and trivalent. Chemical processes affecting these states are important in fate determination. Hexavalent chromium is quite soluble, and reacts with reducing materials to form trivalent chromium, which is primarily hydrolized and precipitates as chromium hydroxide. This precipitation is felt to be the dominant fate process, and the trivalent form is the most stable under normal water conditions. Both forms adsorb only weakly to inorganic solids. Photolysis and volatilization are not considered important fate processes (Chapman et al. 1979).

As an essential nutrient, chromium is bioaccumulated by both flora and fauna to greater concentrations than in the water column, although it is generally less than those in sediments. There is no evidence that methylation occurs, although its occurrence in reducing environments has been speculated (Callahan et al. 1979).

There appears to be little concern about chromium at the moment. Konasewich et al. (1982) do not consider it a metal of concern because levels within Puget Sound sediments fall within normal expected levels. Dexter et al. (1981) and Crecelius (pers. comm.) do not consider it of concern.

Sources and Distribution. Potential sources include automotive repair shops, electroplating industries, carwashes and landfill leachate. Chromium has also been observed in small concentrations in sewage treatment plant effluent.

Information Gaps.

- o Chromium levels in the water column are not well known, but levels in sediments appear normal.

Copper

Properties and Fate. Copper is one of the most toxic metals to marine organisms, but its toxicity is dependent on chemical speciation. Fate is determined by several processes including complex formation, adsorption to sediments, and bioaccumulation. The tendency for copper to form complexes is very important in precipitation. In unpolluted water, adsorption of copper to clay and iron and manganese oxides is the dominant process; in polluted areas, adsorption to organic materials is dominant. Relatively small changes in pH, redox potential, salinity or other factors may result in its transfer from one environmental compartment to another. Biological impact is therefore complex and variable (Konasewich et al. 1982).

Copper is strongly bioaccumulated by both plants and animals, but bioaccumulation occurs to a much greater extent in benthic invertebrates than in fishes. Absorption from the water is important for some species, but for the majority, diet is the main mechanism for accumulation. Copper is apparently not biomagnified (Callahan et al. 1979). Depuration can occur, but it is affected by many factors (Konasewich et al. 1982). Photolysis and volatilization are not considered important fate processes.

In Puget Sound, upwelling may be an important process for freeing copper from the sediments. Important areas of possible pollutant upwelling include West Point and Alki Point. Dissolved oxygen levels and salt wedge penetration in the lower Duwamish River could also affect copper mobilization, particularly at the "toe" of the wedge where salinity is increased (Konasewich et al. 1982).

Sources and Distribution. Copper sources are natural as well as anthropogenic. Natural sources include riverine and atmospheric input, shoreline erosion and advection. Input from anthropogenic sources includes sewage treatment plants, ore smelting, coal burning, clothes laundering, leather processing plants, and pipe leaching (Sittig 1980; Metro 1980). Dexter et al. (1981) estimate inputs from natural sources to be approximately 667 tons per year, compared to anthropogenic inputs of 66 tons per year. Other budgets are listed by Konasewich et al. (1982).

Dexter et al. (1981) have summarized known copper concentrations in sediments, in the water column, and on suspended par- ticulates for all major areas of Puget Sound. They also estimate inputs for various natural and anthropogenic sources. Local anthropogenic input was noted in western Sinclair Inlet, but the lower reaches of the Duwamish River and Commencement Bay showed the highest recorded levels. Elevated concentrations were also observed in the Central Basin near the West Point outfall.

Copper is considered a contaminant of concern by Konasewich et al. (1982) because it exceeds the EPA "heavily polluted" levels in many areas of the sediments, and salt water invertebrates are particularly sensitive to copper and copper speciation. Crecelius (pers. comm.) also considers it to be a metal of potential concern, because of elevated concentrations in water and sediments, although biota do not appear to be directly harmed.

Information Gaps.

- Copper levels in sediments have been measured, but levels in water are not well described.

Lead

Properties and Fate. Chemical speciation affects transport and fate of lead, and may also affect toxicity and bioavailability. At pH values of 7.5-8.5 (ambient Puget Sound levels), lead exists predominately as free lead. Free metal ion concentrations are highest at a 1:1 seawater to freshwater ratio, and the most toxic effects would occur at this range, probably within an estuarine environment.

Adsorption is an important process in Puget Sound (Konasewich et al. 1982). Lead tends to form complexes, and adsorption to inorganic solids, organic materials and hydrous iron and manganese oxides controls lead's mobility. Adsorption and sediment enrichment are important fates in natural waters, but in polluted areas precipitation may be an important process in controlling mobility. Adsorption is highly pH-dependent; lead is more mobile in acidic water.

Volatilization is probably not an important fate process except for alkylated lead compounds. Photolysis is important in determining the form in which lead enters the water, but its importance within the water is unknown.

Marine plants and invertebrates bioaccumulate lead to a greater extent than fish, but it is not biomagnified, and bioconcentration decreases with increased trophic level. Benthic microorganisms can methylate lead, resulting in the more toxic and volatile compound tetramethyl lead. This may be a mechanism for lead removal from the sediments (Callahan et al. 1979).

Sources and Distribution. Lead sources are both natural and anthropogenic. Anthropogenic sources include combustion of leaded gasoline, ore smelting, sewage treatment plant effluent, urban runoff, paint and battery manufacturing plants and similar sources (Sittig 1980).

Konasewich et al. (1982) estimate loadings from anthropogenic sources. Dexter et al. (1981) estimate loadings from both anthropogenic sources and natural sources such as advection, riverine input and shoreline erosion. Crecelius (pers. comm.) estimates a mass balance, and indicates atmospheric input is significant. The main removal mechanism from the water column appears to be sedimentation. Although anthropogenic input is small relative to natural sources, obvious contamination exists in localized areas.

Lead is one of the metals receiving greater attention in Puget Sound. It has been observed in high concentrations in nearly all urban area sediments. Dexter et al. (1981) summarize known lead levels in sediments (and water and suspended matter where available) for all major areas of Puget Sound. Malins et al. (1982a) summarize concentration data and discuss contaminants in relation to biological abnormalities. Health effects are discussed by Sittig (1980).

Especially high lead levels were observed in Hylebos and City Waterways sediments, but highest concentrations were noted in the lower Duwamish River sediments. Metal concentrations in the water column have received much less attention.

Konasewich et al. (1982) consider lead to be a contaminant of concern because of the heavy concentrations observed in the sediments. Crecelius (pers. comm.) considers it to be a metal of some concern that should be examined in more detail because lead levels are elevated in sediments, the water column, and biota.

Information Gaps.

- Alkyl lead compounds are probably quite toxic, and there is uncertainty about the process of lead alkylation in Puget Sound.

Mercury

Properties and Fates. Mercury has been well researched in comparison to many other metals. The great majority is rapidly removed from the water column by strong adsorption to particulates, and sediments are the primary sink (Callahan et al. 1979). However, rapid decreases in Puget Sound sediments have been documented, indicating either methylation or dissolution is occurring, and that the sediments in Puget Sound may not be a permanent sink (Konasewich et al. 1982).

Transformation processes in the sediments include precipitation as HgS in a reducing environment, and methylation by bacteria. Methylation potential is increased in areas of highly organic sediments favoring bacterial growth. These processes may release ionic or metallic mercury back into the water

column. Resuspension of sediments by organisms or turbulence can also release compounds to the water.

Mercury adsorbed to sediments in river water may dissolve when it reaches an estuary, and dissolved levels tend to be higher in estuaries than in either inflowing rivers or the ocean receiving waters.

Photolysis is of importance in the atmosphere, and may affect aquatic fates as well. Volatilization is probably an important process for the movement in and out of the aquatic environment, particularly for methylmercury.

Mercury is strongly bioaccumulated by absorption from water and through the food chain. Most bioaccumulation is connected to methylated forms of mercury, which have a half-life of 1-3 years in most aquatic organisms. Uptake and release of mercury also are affected by season and life state of the organisms. Mercury is one of the few contaminants that is also biomagnified.

Marine invertebrates have some ability to detoxify low level chronic pollution by means of metal binding proteins. There is also some interaction between selenium and mercury, which appears to protect marine organisms from mercury exposure to some extent, although the mechanism is not well understood.

Sources and Distribution. Both natural and anthropogenic sources contribute to mercury loadings. Natural sources include volcanic activity and leaching of natural deposits. Anthropogenic sources include industrial processes such as manufacture of electrical equipment, chlorine, caustic soda, paint, pulp and paper, drugs, smelting and other sources (Sittig 1980). Possible sources in Puget Sound include chlor-alkali plants and sewage treatment plants, smelter stack dust, and industrial discharges to the Duwamish River (Konasewich et al. 1982).

Dexter et al. (1981) and Malins et al. (1982a) summarize mercury levels in sediments for all major areas of the Sound. Mercury has been observed in high concentrations in nearly all Puget Sound urban areas. Highest concentrations were found in the lower Duwamish River estuary sediments, but high levels have also been found in Sinclair Inlet, Hylebos and City Waterways, and Elliott Bay sediments. Crecelius et al. (1975) indicate that mercury in sediments of Bellingham Bay had a half-life of about 1.3 years; elevated mercury levels have also been noted in the water column and organisms (Crecelius pers. comm.).

Konasewich et al. (1982) consider mercury to be a contaminant of concern in Puget Sound because of its toxicity and potential effects on consumers of aquatic life. Because it has been observed at elevated concentrations in water, sediment and organisms, Crecelius (pers. comm.) considers mercury to be a metal of concern, which should be researched in more detail.

Mercury is also one of the four compounds on the priority pollutant listing singled out by Chapman et al. (1979) as being of special significance because of its high toxicity, demonstrated presence in effluent, ability to accumulate in sediments and biota, and because it is one of the few pollutants known to be biomagnified.

Information Gaps.

- Mercury use and discharge have been reduced in the last few years, and the environmental threat may be reduced. However, dispersal and levels of mercury within Puget Sound biota are not well documented. Determination of levels in edible species is of most importance.

Silver

Properties and Fates. Speciation of silver is important in determining its availability to organisms. A number of factors influence speciation including pH, oxidation/reduction state, ionic strength, and concentration of silver and other cations. Silver is strongly adsorbed by manganese dioxide and also by ferric hydroxide and clays, but exposure to seawater enhances release of silver from sediments, due to displacement of silver by other cations. Adsorption studies by Kharkar et al. (1968; in Konasewich et al. 1982) indicate that stream-supplied particulates, rather than acting as binding sites for silver, may actually contribute dissolved silver to the oceans. Adsorption and precipitation with halides is probably the dominant control on silver mobility. Photolysis and volatilization are probably not significant fate processes.

Bioaccumulation occurs to a lesser degree than with the metals previously discussed. It is greater in aquatic fauna than flora, but most silver remains in the sediments. Bioaccumulation appears to be mainly from the water. Depuration is slow, and biotransformation to methylated forms of silver in the sediments is unlikely.

Sources and Distribution. Silver sources are both natural and anthropogenic. The latter include effluent from electroplating, paint, photofinishing, and similar industries, (Sittig 1980) as well as sewer outfalls. Callahan et al. (1979) provide fate information and toxicity. Fate processes and the significance of silver to Puget Sound are discussed in Konasewich et al. (1982). Malins et al. (1982a) provide information on silver concentrations in various Puget Sound sediments, and discuss bioabnormalities observed in areas of contaminated sediments. Sittig (1980) provides information on health effects of silver. Chapman et al. (1979) discuss silver content of Metro effluent.

Silver levels in Puget Sound sediments appear highest in southwest Sinclair Inlet and City and Sitcum Waterways of

Commencement Bay. Concentrations in biota appear highest in Sinclair and Case Inlets (Konasewich et al. 1982).

Silver is considered one of the most toxic of the heavy metals and was chosen as a contaminant of concern by Konasewich et al. (1982) on the basis of the fact that high concentrations have been found in Puget Sound sediments. Dexter et al. (1981) consider data on silver to be limited and of unknown quality, but do not discuss it to any extent in their summary of Puget Sound contaminants because it appears to be producing only minor regional impacts (usually less than twice the criteria level). They do, however, indicate it has been observed in excess in four urban embayments (Elliott and Commencement Bays and Budd and Sinclair Inlets). Crecelius (pers. comm.) considers silver to be a metal of some concern that should be considered further because of its elevation in water, sediments, and biota.

Information Gaps.

- o Silver levels seem to be somewhat in question, and measurements are limited, especially for water and biota.
- o Adsorption mechanisms in estuarine and marine waters are not fully understood.
- o Sources of silver may not be well identified.

Selenium

Properties and Fates. Selenium is very soluble, and most is probably transported in dissolved form as selenite or selenate. Selenium is sensitive to environmental changes, and speciation is important for toxicity and bioaccumulation. As selenite is more toxic than selenate, and may be more persistent in deeper water in Puget Sound, deep water and benthic organisms may be more affected by selenium than pelagic ones (Konasewich et al. 1982).

Under reducing conditions selenium can form metal selenides, most of which have very low water solubility. In oxidizing conditions, adsorption or precipitation is probably the major control on its mobility. Metal oxides adsorb selenium strongly; clays and organic materials do so to a lesser degree. The pH is also important, and selenium is probably quite mobile in clays, especially in alkaline situations. Only in areas of high hydrous iron oxide concentrations would selenium be adsorbed into the bed sediments. Puget Sound data indicate that sediments having high selenium concentrations tend to have low sand/mud ratios, small particle size, and high organic carbon content (Malins et al. 1980 in Konasewich et al. 1981). Photolysis is not an important fate process (Konasewich et al. 1982; Callahan et al. 1979).

Bioaccumulation occurs in both flora and fauna, but it is likely that fauna accumulate primarily via the food chain rather than by uptake from the water. Accumulation is generally low. In some instances bioaccumulation is strongly correlated to concentration of other heavy metals in the organism. Selenium has been shown to inhibit mercury accumulation in some cases.

Biomethylation within the sediments by microorganisms can produce volatile compounds, allowing remobilization of selenium. In a reducing environment, selenium can be converted to a volatile form (H_2Se), and Konasewich et al. (1982) indicate the potential for such conditions in Elliott and Commencement Bays, particularly near outfall locations.

Sources and Distribution. Selenium sources are both natural and anthropogenic. Natural sources include soils and volcanic activity. Anthropogenic sources include: smelting and refining of copper, lead, and zinc; manufacture of glass ceramics, iron and steel alloys, pigments and semiconductors; and fossil fuel combustion (Sittig 1980; Konasewich et al. 1982).

Selenium was selected as a contaminant of concern by Konasewich et al. (1982) because it is found in Puget Sound sediment at levels much higher than those in deep sediments or the earth's crust. Little local data on selenium are readily available. Selenium was not discussed by Dexter et al. (1981) in their summary of knowledge of Puget Sound contaminants, because they felt no reliable data were currently available. It was not observed in Metro effluent (Chapman et al. 1979), although it is an important constituent of some shampoos and hair products.

Information Gaps.

- Reliable data concerning concentrations in water and sediments, and levels and areas of contamination, do not seem to be available for selenium.

Zinc

Properties and Fates. Zinc is readily transported and one of the most mobile of heavy metals. It adsorbs to clay, hydrous iron and manganese oxides, and organic materials, but adsorption is influenced by concentrations of materials. Adsorption increases with pH, and increased Eh releases zinc to the water column. In a reducing situation, or in areas of high zinc concentration, precipitation of zinc sulfide is important in reducing zinc mobility.

The release of zinc from sediments is dependent on a combination of ion exchange and complex formation; stability of the complex determines solubility. Generally, organic material in polluted waters affects the form in which zinc is present,

and complexes will predominate. In unpolluted areas, zinc normally will be a divalent cation, and easily adsorbed. Volatilization and photolysis do not appear to be important fate processes (Callahan et al. 1979).

Zinc is strongly bioaccumulated by marine biota, and fish may accumulate it from both food and water, but bioaccumulation appears to be a minor sink compared to the sediments. No biomethylation has been observed (Callahan et al. 1979).

Sources and Distribution. Zinc is produced in alloy production and plating processes (Sittig 1980). The greatest anthropogenic source appears to be atmospheric (Dexter et al. 1981), and dust from the Harbor Island smelter is a major source of pollution in the Duwamish estuary area. CSO and storm drains, such as the Diagonal Way overflow, Hanford Street overflow, and Denny Way overflow, have also been identified as contributors to zinc contamination in the Duwamish estuary area. Dexter et al. (1981) summarize concentrations of zinc in water and suspended particulate matter for various areas of Puget Sound and estimate inputs for individual rivers, municipal and industrial effluent, storm drains, and CSOs. They provide an estimation of annual loading for both natural (riverine input, erosion and advection) and anthropogenic sources. Zinc loading is estimated by Dexter et al. (1981) to be much greater than that of arsenic, copper or mercury, with the bulk of the input projected to come from natural sources.

Highest levels were observed in the Duwamish River estuary, but high levels have also been observed in Hylebos and City Waterways of Commencement Bay, in Budd and Sinclair Inlets, and in Elliott Bay.

Zinc, although elevated in the sediments, has not been identified as a contaminant of concern by Konasewich et al. (1982). Because zinc does not appear elevated to any appreciable extent in the water or biota, Crecelius (pers. comm.) considered it to be of little concern.

Information Gaps.

- Relative to other pollutants, zinc does not appear to be as great a problem, and no recommendations for additional studies on zinc in the Puget Sound area have been noted in the literature.

Nickel, Thallium and Beryllium

Properties and Fates. Nickel is the most mobile of the heavy metals, and adsorption and precipitation do not appear as important as with other heavy metals. Adsorption to organic materials and hydrous iron and manganese oxides is the dominant factor in its mobility, and partitioning into dissolved and

particulate fractions is related to iron, manganese and suspended material concentrations. Photolysis and volatilization are not important fate processes. Nickel is bioaccumulated, but concentrations indicate that neither this nor biotransformation is a dominant process.

Thallium behavior is not well documented, but it appears that adsorption to clay and hydrous metal oxides and bioaccumulation are the primary processes for removal from the water column in aerobic waters. In anaerobic areas, precipitation as a sulfide may be important. Photolysis and volatilization are unimportant fate processes. Thallium is quickly bioaccumulated by both flora and fauna, but there is no evidence that biotransformation is important.

Beryllium has very low solubility in water, and tends to be in particulate form, either adsorbed to clays or to other mineral surfaces, rather than in dissolved form. Under normal pH conditions it is hydrolized to form insoluble compounds; this is the controlling mechanism for beryllium in the aquatic environment. Photolysis and volatilization are not considered important fates. Beryllium is bioaccumulated in low amounts, but there is no evidence of biomagnification through the food chain. Nothing on biotransformation processes has been reported.

Sources and Distribution. Nickel is used in alloys and electroplating. Beryllium is used in production of alloys, copper and brass, and thallium is used in alloys and electronics production (Sittig 1980). Nickel is used in electroplating facilities. Thallium compounds are found in insecticides, depilatories and rat poisons. Treatment plant outfalls and riverine input are likely sources of input (Metro 1980).

Because neither nickel nor beryllium concentrations were elevated above expected background levels, and (presumably) because nothing of significant concern was known about thallium, none of these is considered to be contaminants of concern by Konasewich et al. (1982). Dexter et al. (1981) do not discuss thallium in their summary of Puget Sound contaminants because of the lack of reliable data, do not discuss nickel because concentrations were not found to exceed the criteria, and do not discuss beryllium because data were considered to be limited and impacts minor. Crecelius (pers. comm.) does not consider these three heavy metals to be of concern because no high concentrations were observed in water sediment or biota. It would appear that, relative to other metals, these three are of minor significance.

Information Gaps.

- No critical issues are identified for these substances at present.

Antimony

Properties and Fates. Antimony reacts somewhat differently in the environment than the materials described above. Antimony has a high solubility and is primarily transported in solution. Adsorption to clay and other minerals is normally the most important process for removing it from solution, although precipitation with manganese and aluminum oxides and bioaccumulation may also contribute to removal. It is probably only temporarily resident in sediments. Reducing environments, such as found in bed sediments, may result in formation of the compound stibine, and remobilize the antimony previously removed from solution. It is speculated that heavy metals in solution reduce antimony's mobility. Antimony is only slightly bioaccumulated. Some metabolic transformations by bacteria (of unknown distribution and importance) have been reported, and biomethylation is also thought to be possible, but undemonstrated. Photolysis is of little importance as a fate process.

Sources and Distribution. Antimony sources are both natural and anthropogenic. Potential anthropogenic sources include paper manufacturing, munitions, and metal alloy fabrication (Metro 1980; Sittig 1980). Smelting may also produce antimony. The northern rivers (Snohomish, Skagit, Stillaguamish and Duwamish) provide concentrations approximately six times greater than that of the southern rivers (Puyallup, Nisqually, Dosewallips, and Duckabush). This seems to be primarily a reflection of mineral differences within the drainage basins, rather than anthropogenic sources.

Dexter et al. (1981) provide data on antimony levels in many areas of Puget Sound sediments, and note that high localized concentrations occur in Commencement Bay and "probably" in the Hylebos and City Waterways as well. These concentrations are attributed to liquid and slag discharges of the ASARCO smelter.

Konasewich et al. (1982) classify antimony as a Class 2 compound (of possible concern, but difficult to assess as a hazard and existing in very low concentrations). Antimony has not been noted in West Point or Renton treatment plant effluents (Chapman et al. 1979), and is not considered to be of concern by Crecelius (pers. comm.) because it is apparently not elevated in organisms.

Information Gaps.

- There is little information on antimony concentrations in the water column.

Cyanides and Asbestos

Properties and Fates. Cyanides are a diverse group having varied environmental fates. They are adsorbed by organics and biological solids and to a lesser extent by clays, but they have a high solubility in water, and adsorption is not considered an important process in aquatic environments. Most free cyanide exists as HCN, a quite volatile compound at a pH of less than 10. Biodegradation and volatilization appear to be the most important fate processes. The simple metal cyanides are insoluble and probably accumulate in the sediments, whereas complex metallocyanides are transported in solution in the water. Photolysis can break down some metallocyanides, and at low concentrations, cyanides are biodegraded by almost all organisms. Cyanide is not bioaccumulated because it is either quickly metabolized or the organism dies due to toxicity (Callahan et al. 1979).

Asbestos is a generic term for a number of hydrated fibrous silicates. It is mineralogically stable, almost indestructible, and not likely to degrade significantly. Photolysis does not occur, and volatilization is an unimportant fate process. Asbestos appears to remain in suspension in water for long intervals until changes in flow or coagulation allow settling. It is considered nondegradable by aquatic organisms, and does not bioaccumulate (Callahan et al. 1979).

Sources and Distribution. Asbestos sources include roofing products and leaching from pipes or ores. Cyanides result from: photofinishing; electroplating; steel, plastics and chemical manufacturing; commercial testing laboratories; and similar industries (Metro 1980; Sittig 1980). Neither cyanides nor asbestos have been considered by Crecelius (pers. comm.) or Konasewich et al. (1982) as of potential concern. Neither compound was noted to occur in Metro effluent by Chapman et al. (1979), although effluent analyses in the 301(h) applications indicate that cyanide has been observed in the effluent in both wet and dry weather.

Information Gaps.

- As neither substance seems to be a present problem, no important gaps appear to exist at this time.

Particulate Matter

Particulates play an important role in the aquatic environment for a number of reasons. Although not toxic themselves, they have effects of their own on both the water column and sediments. Particulates suspended in the water column decrease water clarity, affect light penetration, and may clog respiratory and feeding organs, which in turn affect the biotic community in a number of ways. If and when particulates settle out of the water column, they may cause outright burial of sessile

organisms if the particulate load is heavy enough. Heavy sedimentation may change sediment grain size, thereby affecting the community structure and causing formation of a new, soft bottom association.

Particulates may adsorb toxic materials and are often the main vehicle by which toxic materials enter the aquatic environment. As particulates become part of the sediments, they act as a major sink for many contaminants. Understanding reaction within the sediment is often the key to understanding contaminant fate processes. In addition, sediments are often sampled to assess contaminant levels.

Properties and Fates

The relationship and exchange of materials between the dissolved and particulate state in the water column is important, because the state of a contaminant affects its method of transport and distribution, as well as its availability to the biota. Suspended particles in water thus play a major role in regulating chemical form, distribution, and deposition of trace metals and other materials, especially in coastal areas (Massoth et al. 1982).

One of the most important aspects of particulates is their tendency to adsorb contaminants such as pesticides, PCBs, heavy metals, and organic compounds. Two exchange processes have been identified as being of import in Puget Sound and both are related to particulates: the adsorption/release interactions between water and suspended material in estuaries, and the mobilization of contaminants from the sediments (Dexter et al. 1981).

Fine-grained sediments, such as clays, tend to accumulate increased concentrations of metals. There is an especially strong correlation between grain size and concentration for some metals, such as arsenic, antimony, and copper, and less for others, such as mercury and iron (Dexter et al. 1981). Because clay particles are negatively charged, many substances bond to them, and as they are finer in size, they tend to remain suspended for longer intervals and thus become more widely transported.

The settling rate of particles is affected by speed of current, water turbulence, flocculation rate, salinity, particle size, and other factors. When particulates enter salt water, they tend to be attracted together and form floc, which tends to settle out more rapidly. This decreases concentration of adsorbed contaminants in the water column and increases concentration in the sediments. These particles, as a major food source for some marine organisms, are an important vehicle for passing contaminants into the food chain in various species. Deposition of particulates results in greater exposure of benthic organisms to toxicants.

Pollutants entering the water in turbulent areas tend to be rapidly diluted, and do not impart high local concentrations in the water column or sediments (Dexter et al. 1981). For this reason, Crecelius (pers. comm.) indicates that outfall location in most areas of the Central Basin main channel is probably not important, because the pollutants become mixed and eventually deposit in fine sediments of the Central Basin between Tacoma and Seattle, regardless of outfall location. Settling of fine sediments occurs in quiet areas, such as Quartermaster Harbor, and may result in highly localized concentrations of contaminants which had their origin elsewhere. Curl (1982) has hypothesized that the sill across Admiralty Inlet greatly influences the deposition of particulates in the Central Basin. Bottom water in the Sound is renewed when spring tides exceed 3.5 m, or during neap flood tides when vertical mixing allows undiluted water from outside Admiralty Inlet to enter over the sill and produce density currents. These, together with bottom tidal currents, transport suspended particulates southward. Sediment tends to be retained in the Sound, perhaps in the deeper water off Poverty Bay (Curl 1982). This hypothesis is currently being examined by Pacific Marine Environmental Laboratory (NOAA).

Chemical, physical, and biological reactions within the sediments are also important, and many researchers have noted that a reducing environment may result in mobilization of some metals from sediments to interstitial or overlying water. If the reducing layer is located below an oxidizing layer, mobilization to interstitial water within the sediments will result in precipitation in the upper sediment layers, causing a contaminant buildup which may appear similar to the concentrations found in areas where contamination has increased over time (Dexter et al. 1981). Studies of the sediment/seawater interface and interstitial pore water (Curl 1982) indicate Puget Sound sediments are typically reducing. Reducing sediments have been shown to support enrichments of manganese in the bottom waters. Several trace metals are scavenged by newly formed hydrous manganese oxides in deeper water of Elliott Bay. This reduces the potential for bioaccumulation of these elements, because metals bound to manganese or iron oxides appear less available to organisms than elements bound to organic materials (organic flocculants). However, this process may be counteracted in some areas by other fate processes, e.g., Curl (1982) also reported that organic floc formation was a significant fate mechanism for suspended matter in the Duwamish River estuary.

Sampling of sediments can produce deceptive results, not only through competing or undetected fate processes, but also because different core samplers may compress sediments and distort time-depth correlations. Crecelius (pers. comm.) indicated box cores tended to cause less compression of sediments. Data interpretation can also be skewed if sediment size is not taken into account; Dexter et al. (1981) point out that variations in concentration of at least a factor or two may result solely from grain-size differences. A low concentration

of contaminant in large-grained sediment may occur in an area of significant local input, while the same degree of input in a fine-grained area might result in a much higher concentration. Presence of organic matter is also a factor in influencing particle chemistry.

Sediment concentrations are often used to evaluate contamination levels, but if grain size, sediment depth, and other factors have not been taken into account, comparisons of concentrations between areas or between studies may be meaningless. For example, the Metro TPPS program analyzed sediments at 168 stations for total carbon, 16 heavy metals, pesticides, and several organic compounds. The majority of the stations were along the east shoreline of the Central Basin between Edmonds and Alki Point. If data from all stations are compared, there is no correlation between sediment grain size and surface sediment chemistry. For stations off Edmonds, copper, lead, mercury, and silver concentrations in the surface layer correlated well with grain size. Similarly, copper concentration in deep (preindustrial) sediments correlated well with grain size (Romberg, pers. comm.). Clearly there are a number of factors to be considered in evaluating contaminant levels and in comparing data taken at various places and times by researchers with varying methodologies. In addition, interactions of metals and other contaminants within Puget Sound sediments are not well researched, although these processes appear to be critical.

Sources and Distribution

Riverine inputs and shoreline erosion are considered to be the major sources of sediment input; biological production and advection are not considered significant processes (Dexter et al. 1981). Wang (1975 in Dexter et al. 1981) estimates 75 percent of sediments originate from shoreline erosion.

Sediment discharge rates for major Puget Sound rivers, shoreline erosion rates and input estimates by area, estimated sediment budget, and a summary of sediment transport studies are given in Dexter et al. (1981). Sedimentation rate estimates range from 0.8 mm/year (Hood Canal area) to 20 mm/year (East Passage), with the Sound averaging 5.6 mm/year.

Recent sedimentation studies have been made for some areas of Puget Sound. Data collected by the Metro TPPS program indicate that sedimentation rates on the average appear uniform at deep core stations south of West Point, and a little higher than at deep core stations located north of West Point (Romberg pers. comm.). Baker and Walker (1982) discuss interrelationships between salinity, current, and suspended particulates for surface and bottom waters in Commencement Bay. Massoth et al. (1982) describe flocculation, sedimentation, and trace element fates in the Duwamish River estuary. Curl (1982) discusses

flocculation processes in the Duwamish estuary, and trace element scavenging in Elliott Bay. Baker (1982) describes particulate matter reactions in Elliott Bay; characterizes sediment content, size, minerology, and flux; and contrasts wet and dry weather input.

Adsorption to sediments is a primary transport mechanism for many materials, and often higher concentrations of contaminants are associated with the suspended sediment than with the water. However, Dexter et al. (1981) note that because suspended sediment concentrations in most parts of Puget Sound are quite low, even for compounds with a strong tendency to adsorb, the greater portion may remain in dissolved form. Once away from areas of high suspended sediment, the primary transport mechanism is advection.

Information Gaps

- Conditions and reactions affecting contaminants within Puget Sound sediments are not well understood. These determine the contaminant's ultimate bioavailability.
- Sedimentation rates and pollutant concentrations within sediment layers are not well documented. The number of sediment samples is also limited, and data are not always comparable from one location to another.
- Contaminants associated with suspended matter in the water column are even less well studied than sediment concentrations.

Sediment Chemistry Investigations

A number of investigations have been conducted in the study area on the levels of contamination in sediments. These range from highly localized investigations of proposed dredging or spoil disposal sites to regional investigations such as the ongoing Metro TPPS and Seahurst baseline information programs. Much of the information from previous studies has recently been reviewed by Konasewich et al. (1982), Malins et al. (1982a), Dexter et al. (1981), and Riley et al. (1981). Sediment types in the study area have been mapped by WDF in draft form (Dahlgren pers. comm.) and by Roberts (1979).

Ongoing Investigations

Metro TPPS Program. Although the Metro TPPS program has been completed, the TPPS report had not been produced at the time of preparation of this report. The following summary results from discussions with Romberg (pers. comm.).

The sediment analysis focused on the Denny Way CSO and the West Point outfall, therefore, 113 of 168 stations were located

on the east side of the Central Basin between Edmonds and Alki Point. The remaining 55 stations were located in the main channel from Tacoma Narrows to Admiralty Inlet, and in Colvos Passage, Lake Union, Lake Union Ship Canal, and the Duwamish Waterways.

The top 2 cm of sediment at each station were sampled and analyzed for grain size, total carbon, 16 heavy metals, pesticides, and other EPA priority pollutants. Deep cores were taken at 21 stations to obtain information on background (preindustrial) concentrations and sediment deposition rates.

The TPPS report will plot enrichment factors for arsenic, copper, lead, mercury, silver, and zinc. The data also can be used to plot concentration isopleths for the 16 heavy metals, DDT, PCB, phthalate esters, combustion PNAs, and other aromatics.

Metro Seahurst Baseline Study. The 3-year Metro Seahurst baseline study includes 2 years of data collection. The first year was completed in March 1983, and an annual report should be available by August 1983. The sediment investigation studies include the sampling of 105 stations located between Blake Island and Commencement Bay. The majority of the stations are placed in East Passage, with a few in Colvos Passage. Stations were selected from areas expected to contain high concentrations of contaminants, and additional sampling will be undertaken as the more heavily contaminated areas are located. Samples are being obtained with a 0.1 m^2 Van Veen grab, but gravity, box, and Kasten cores (50-190 cm) are also being collected. Analyses of the Van Veen samples include 14 metals and a complete scan for organics, so that at a future date, additional organic contaminants are identified when spectra for these become available. Some unanalyzed samples are also being frozen for future reference if needed. Grain size analyses are being made. Determination of chemical speciation is not possible for many contaminants.

Completed Work

Two major reports summarize recent studies on distribution and concentration of pollutants in sediments. Dexter et al. (1981) average the concentrations of selected metals (Zn, As, Pb, Hg and Cu), PCBs, CBDs, and arenes (multi-ringed aromatic hydrocarbons) in sediments for various areas within the major Puget Sound embayments. Except for metals, individual compounds are not distinguished, but the report provides a semi-quantitative comparison of levels of these pollutants in sediments of various Puget Sound areas.

Konasewich et al. (1982) review sediment contamination studies from the perspective of the contaminant rather than the

location. Contaminants in sediments were ranked according to hazard, and those of greatest concern (based on toxicity, properties, and concentrations) are described in terms of fate processes, toxicity, properties, and sources. These include PCBs, the PAHs, metals (As, Cd, Cu, Pb, Hg, Se and Ag), DDT, and several other groups of chlorinated compounds.

Malins et al. (1982a) obtained sediment samples (with 0.1 m^2 Van Veen grab) in 14 sample locations which included both urban and nonurban areas. Locations included: Elliott, Commencement, Discovery, and Liberty Bays; Budd, Case and Sinclair Inlets; Everett; Bellingham; Shelton; Port Madison; Port Angeles; and Ebey Slough. Sample site selection was based on known or suspected depositional areas, and the majority of the sites were selected to reflect "worst case" situations. Temperature, salinity, and DO were also measured at or near the sample areas.

Results showed that many compounds vary extensively within, as well as between, embayments; the wide ranges suggest highly localized depositional patterns. Several hundreds of compounds were found, and many remain unidentified/unconfirmed because reference mass spectra have not been published. Highest concentrations of aromatic hydrocarbons were found in Elliott and Commencement Bays (up to 30 times the mean for reference areas of Port Madison and Case Inlet). PCBs in Elliott and Commencement Bays and Sinclair Inlet were 300 times those of the reference areas. CBDs and HCBs were ubiquitous, although only Commencement Bay samples greatly exceeded those of the reference areas. Chlorinated pesticide levels were low, but did exceed the reference areas by 20 times in Elliott and Commencement Bays. Metal concentrations varied with the embayment; mercury, lead, arsenic, silver, and cadmium were generally distributed throughout the Sound. Mercury was highest in Bellingham Bay; lead highest in Elliott Bay, Commencement Bay and Sinclair Inlet; arsenic in Elliott Bay and Commencement Bay; silver and cadmium were generally similar in both urban and reference areas. Cluster and principal components analyses of the sediment chemistry data yielded eight cluster groups of sampling stations and four principal component axes.

Riley et al. (1980) sampled a total of nine stations in Elliott Bay (three), Commencement Bay (three), Sinclair Inlet (one), Budd Inlet (one), and a reference area, Port Madison (one). To determine pollutant concentrations in suspended matter and water, samples were analyzed to determine quantity and type of contamination. Suspended matter from both Elliott Bay and Commencement Bay contained metal contaminants. Hylebos and Blair Waterway samples additionally showed aromatic hydrocarbons. There is not necessarily a direct correlation between contaminant levels in the water column and the sediment. A subsequent study was conducted that provided sediment chemistry data at approximately the same station locations in Hylebos and Blair Waterways.

Riley et al. (1981) collected 30-50 cm sediment cores at 10 sites in the Hylebos and Blair Waterways. Suspended matter and water samples were also analyzed to aid in evaluation of the chemistry of the pollutant compounds. Cores in some areas represented up to 50 years of sedimentation; historical and current input and distribution were analyzed. Highest concentrations of organics were recorded for the most recent sediments. Major classes in both sediments and suspended matter included aromatic hydrocarbons, PCBs, and CBDs; water concentrations indicated current sources of CBDs and PCBs in the waterways.

Environmental Context

Several dynamic chemical and physical factors in the environment influence the chemical-physical state (compartmental distribution and chemical species) of a chemical compound; e.g., pH, Eh, dissolved oxygen, redox conditions, suspended solids concentrations, salinity, temperature, and numerous other factors. These environmental conditions also affect biological processes such as feeding, metabolism, and respiration, which in turn affect biological uptake. Other factors influencing biological uptake include: the organism's life history stage, sex, reproductive state, and size. The ability of an organism to take up a chemical compound and the chemical species of the compound helps determine the distribution of the compound in the environment, which in turn plays a feedback role affecting both uptake rate (bioavailability) and speciation of the compound. The physical, chemical, and biological environments are therefore interrelated, and must be viewed as a whole if data are to be understood in a correct context. These interrelationships can be illustrated in a simple way by the diagram in Figure 6-1. Assessment of contaminant concentrations, fates, and effects therefore is difficult.

Applicability of the EPA Priority Pollutant List

Considering that over 3 million compounds are listed in the chemical abstracts, the number of compounds known to be hazardous is quite small. Several characteristics of a compound collectively determine whether the compound constitutes a hazard. These characteristics are some combination of: inherent toxicity of the compound, persistence, ability to bioaccumulate, scale of production, and chance for release to the environment.

Logic along these lines led to the establishment of the EPA priority pollutant list, which is a start toward prioritizing potential concerns. Establishing a list, however, tends to divide things into the categories of "on the list" (therefore by assumption, significant) or "not on the list" (therefore nonsignificant). This thinking may be erroneous, because a number of contaminants not of sufficient national impact to warrant

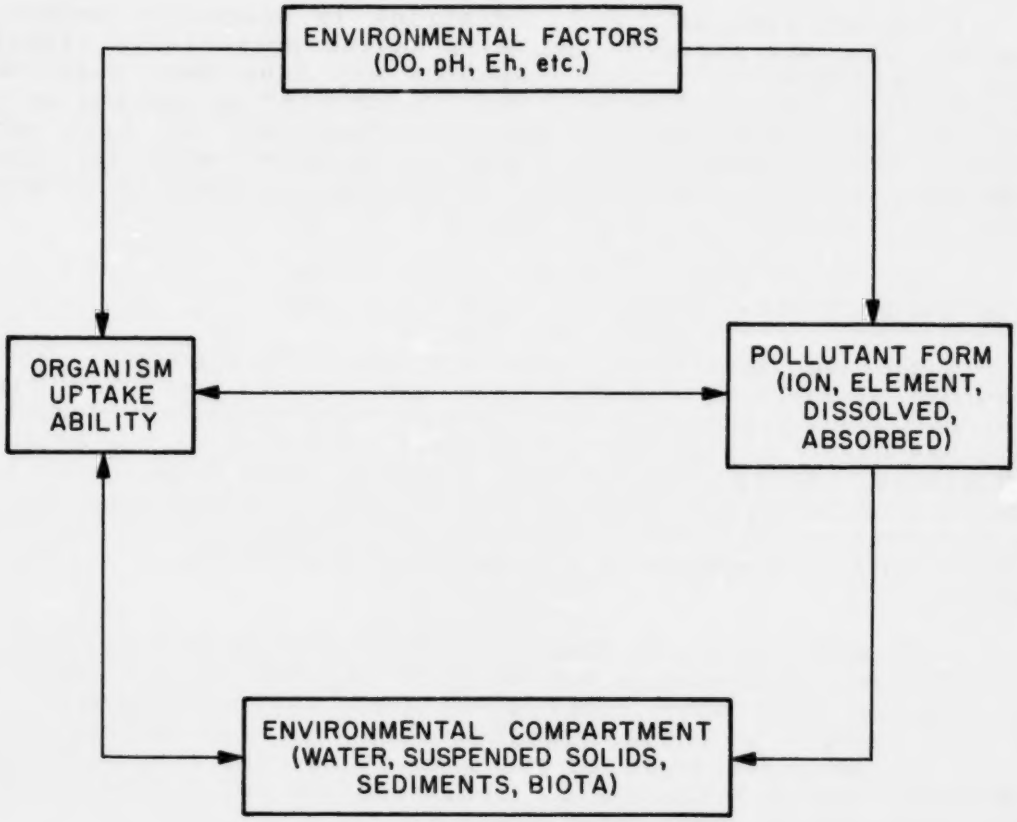

Figure 6-1. Relationship Between Environmental Factors and the Fate of Pollutants

inclusion on such a list may nevertheless be locally significant. Conversely, some listed chemicals may not be relevant locally. Such a list should therefore be used primarily as a starting point for development of a locally relevant list. Konasewich et al. (1982) have made a start in this direction by ranking locally observed contaminants and suggesting compounds requiring additional study (Appendix E).

A closer look at local industries is needed to determine whether they may produce toxicants having potentially significant local impacts. These compounds may have been overlooked because they are not "conventional pollutants" or are not on the priority pollutant listing, and therefore have not been monitored. This information can then be included with applicable compounds already identified, to produce a locally relevant list.

Existing Fate Data

Based on structural similarities in compounds, it is possible to assess probable fate and predict behavior for a compound even though actual research has not been conducted. This has been the case out of necessity for many of the priority pollutants. Where studies have actually been made, they have rarely been performed in Puget Sound, and the conditions may not be relevant to the local situation. In many cases, data were determined for freshwater systems, not for marine or estuarine waters.

Understanding local fate processes is critical, as behavior in different environments may be quite different, and there are indications that some local conditions may be unusual. One obvious example is the unexpectedly high ratio of DDT to DDE in biota. A second example is the loss of mercury from Bellingham sediments, which indicates the sediments are not a final sink as they have been in some other areas.

Rivers discharging into Puget Sound create an estuarine situation at the river mouth where seawater and freshwater interface. Similar mixing may occur in localized areas around wastewater outfalls. The shift to saline water changes water chemistry sufficiently such that a shift in environmental compartment may occur in these areas. Materials such as silver and zinc may be released from suspended sediment into the water column, while polynuclear aromatic hydrocarbons and some other organic compounds may form floc that settles out or precipitates, rapidly removing contaminants from the water. Fate of pollutants in estuarine areas is especially important because these are often nursery areas for young organisms. Similarly, it has been suggested that upwelling areas may free copper and perhaps other materials from particulates. Reactions in upwelling areas also require study.

A number of contaminants produce metabolites which are as toxic or of even greater toxicity than the parent compound, and there is little information concerning the concentration of these compounds. If these relationships are not understood when sampling, the picture obtained may be a false one. Aldrin, for example, is quickly transformed to dieldrin. Sampling of aldrin without dieldrin may indicate an absence of aldrin input, which may not be the case.

Synergistic effects of pollutants are largely unknown for Puget Sound (or elsewhere). These are difficult to assess because there are a large number of potential interactions, and because they may produce sublethal effects which are often less obvious.

Sampling Methodology

Some compounds, such as metals, have been much more extensively sampled than others, and the volume of literature makes them appear of greater importance. A number of contaminants would appear to be little understood, i.e., there is little literature concerning their presence or levels in water, suspended sediment, biota, bottom sediments or effluent. It is not clear whether this is due to their actual absence or to a lack of sampling. In many cases, the latter reason is probably more correct.

Sediment grain-size, organic matter content, depth, and redox conditions within the sediment all affect contaminant concentrations. In addition, the type of sediment sampler used will affect the degree of time/depth distortion in sediment cores. Variations in concentration of a factor or two have been noted to result solely from grain-size differences, as the smaller clay particles tend to adsorb contaminants more easily (Dexter et al. 1981). If variation in sediment size, depth and other factors are not taken into account during data gathering and analysis, comparison of data from various locations (not to mention data from researchers using different methods at differing depths and seasons) can be meaningless, at least for sediments. A real need exists for standardization of these operations so that a baseline data base can be developed and trend determination accurately assessed.

Chlorination of wastewater effluent (and drinking water) affects contaminant levels and fates. It may result in the formation of additional chlorinated compounds, increase levels of other compounds, and even result in production of other priority pollutants. Addition of chlorine to a compound increases its toxicity, lipophilic character, and tendency for bioaccumulation. Formation of these compounds is dependent on length of exposure, amount of free chlorine, and other treatment techniques. Determining effects of chlorination on effluent must occur, therefore, in a sampling regime that faithfully reproduces the conditions effluent is likely to experience.

Concentration in the Environment

A large number of knowledge gaps still remain regarding distribution of pollutants in the environment. With the exception of PCBs, concentrations of organic compounds are poorly documented for all environmental compartments. However, a few general things have been inferred for metals. Although higher concentrations are found in urban areas, in general, concentrations appear at or near natural levels in most areas, and there is an overall predominance of natural over anthropogenic input. Input exceeds assimilation and dilution capacity only in poorly flushed areas in proximity to loading sources (Dexter et al. 1981). No toxic responses in organisms have been identified for metals (Dexter et al. 1981; Crecelius pers. comm.), although in some areas concentrations may exceed criteria for human consumption.

Pollutant loadings of metals, PCBs, pesticides and perhaps a few other compounds as well, have decreased drastically over the last few years. Some compounds, such as PCBs and DDT, are no longer manufactured. Others, such as a number of the pesticides, are greatly restricted in use, or are removed from effluent in greater concentrations due to NPDES requirements. Although trends are not obvious at this point, decreasing levels of these compounds should be found over time.

Summary

Transport, fate, and availability of pollutants to organisms are related. Pollutants in the water column may be transported far from their source and are generally most available to pelagic organisms; those deposited in the sediments may remain in one location for long periods and are generally most directly available to benthic organisms. A number of chemical, physical, and biological processes affect pollutant fate and properties. Physical processes include adsorption, dissolution, sedimentation, and resuspension. Chemical processes include speciation, flocculation, chemical precipitation, diffusion, volatilization, photolysis, reduction/oxidation, and hydrolysis/hydration. Biological processes include bioaccumulation, biotransformation, and biodegradation. The chemical structure of each pollutant determines the effects of these processes and the ultimate fate of the pollutant.

A review of literature on properties, fates, sources, and distribution in Puget Sound for the 126 EPA "priority pollutants," petroleum hydrocarbons, polychlorinated dibenzofurans, and particulates reveals numerous data gaps for most of these pollutants. Behavior of many compounds, and even whole groups, is not well understood. Behavior of an entire group often must be inferred from behavior of a single compound or behavior of related compounds because compound-specific data are not available. In addition, reactions are often site-specific and much

of the known fate information is based on reactions in a freshwater environment. Interactions in the marine environment in general, and in Puget Sound in particular, are not well understood. Relationships between contaminated sediment, benthic uptake, and organism/ecosystem impact are unclear. Synergistic effects of pollutants on organisms or on the ecosystem are essentially unknown. Concentrations of pollutants in biota (with the possible exception of metals and PCBs) are not well known.

Certain compounds appear to be of greater concern than others based on their acute and chronic toxicity, their tendency for persistence and bioaccumulation, and the degree and extent of local contamination. Many of the priority pollutants do not appear to be of local concern, while other pollutants not considered as EPA priority pollutants have greater local impact based on their prevalence and properties. Compounds of the most concern appear to be DDT/DDE, PCBs, chlorinated aliphatics (including chlorinated butadienes), polychlorinated dibenzofurans, polycyclic aromatic hydrocarbons (particularly naphthalenes, fluoranthenes, benzo(a)anthracene, benzo(a)pyrene, and possibly pyrene and chrysene) and, to a lesser extent, heavy metals. Others, such as aldrin/dieldrin, are of potential concern, but additional data are needed to determine their status.

Loading of some groups, such as PCBs and chlorinated pesticides, is expected to decrease over time as manufacture and use of many compounds ceases or is greatly reduced. Loading of other pollutants, such as heavy metals, has already been greatly reduced through imposition of NPDES effluent limitations. Loading of groups such as polycyclic hydrocarbons is not likely to decrease naturally, and may increase with increased urbanization.

Water and sediment reflect localized input of contaminants in many areas. In general, the urbanized areas show highest concentrations, although many substances, particularly "nonconventional" pollutants such as organics, are not well documented and their "lack" of local presence is suspected to be due more to lack of sampling then to lack of contamination.

Elliott Bay and the lower Duwamish River show some of the highest levels of As, Cu, Pb, Hg, Zn, DDT/DDE, PCB, MAHs and PAHs. Commencement Bay and its waterways show some of the highest levels of As, Cu, Pb, Hg, Ag, Zn, Sb, chlordane, PCBs, CBDs, MAHs, and PAHs. Sinclair Inlet shows some of the highest levels of As, Cu, Hg, Ag, Zn, PCBs, and PAHs. High levels of As and Zn have been noted in Budd Inlet as well, and high levels of Hg have been noted in Bellingham Bay. More extensive sampling of sediments in areas such as Bellingham Bay, Everett Harbor, and Hood Canal might show additional high concentrations of these substances. Over 1,000 organic compounds have been identified from urban embayment sediments, and many still have

not been identified. Of these, the polycyclic aromatic hydrocarbons (PAHs) are probably of greatest overall concern because of their diversity, levels of concentration, and potential effects. Studies of these compounds in Puget Sound sediments are limited, and areas of greatest concentration can only be surmised at this point, but it is probably safe to assume that all urban embayments will show some areas of high, localized concentrations, although the compounds may vary.

Chapter 7

IMPACTS OF POLLUTANTS ON BIOTA

Introduction

Identification of linkages between pollutants and effects on organisms, habitats, or beneficial uses is an important part of the predictive process in making water quality management decisions. The first predictive step is to estimate how changes in sediment and water quality parameters resulting from various water quality management options (e.g., increased treatment, waste diversion, or alternative discharge sites) will affect the biota or beneficial uses. This step is generally accomplished by either knowing or predicting the fate of pollutants, pollutant concentrations, and their environmental effects at specified areas. If cause-and-effect relationships are known (change in water quality and its effect on an organism), the circulation and water quality modeling results can then be used to assess the relative biological effects of the water quality management options. The objective of this section is to identify and review available information on the biological impacts of nutrients and toxicants in Puget Sound, and to assess the value of this information in defining cause-and-effect relationships that can be used in making water quality management decisions.

This review is organized according to three biotic groups: fishes, benthic macroinvertebrates, and plankton. Studies of nutrient or pollutant impacts relating to each biotic group are reviewed based on kinds of effects. The following biological effects are addressed in this review:

- Bioaccumulation
- Disease
- Mortality
- Behavioral alterations
- Reproductive success
- Changes in abundance (may result from mortality, behavioral alterations, or reproductive success)
- Trophic effects (e.g., food chain transfer of pollutants, change in production of higher trophic levels).

In general, these effects are broadly organized into studies of ecology, toxicity bioassays, bioaccumulation, and pathology.

Fishes

Ecology

The most extensive studies of fish ecology as a function of pollutant inputs have been conducted to examine possible adverse effects of the discharge of municipal sewage effluent, and the most comprehensive of these have been conducted for Metro. More limited studies of this type have been sponsored by a number of smaller municipalities on Puget Sound. Several studies have attempted to examine possible adverse effects of the industrial discharges of pulp and paper on fish ecology mills at various locations around Puget Sound. In addition, other studies have attempted to establish relationships between the ecology of resident fish communities and the disposal of chemical contaminants in the vicinity of diverse industrial complexes (e.g., Commencement Bay and the lower Duwamish River). Still other studies have been aimed at detecting possible impacts of the disposal of contaminated dredge spoils on the local fish communities. Due to the diverse nature of the pollutants from these various sources and the diverse nature of potential impacts caused by these pollutants, the studies of fish ecology associated with each pollutant source are discussed separately and in detail.

Effects on Fish Ecology in the Vicinity of Municipal Sewage Discharges. The most comprehensive investigations of the ecology of fish communities in the vicinity of municipal sewage outfalls in Puget Sound have been a series of studies (Moulton et al. 1974; Miller et al. 1975; English 1976a; Miller et al. 1977; English and Thorne 1977) conducted for Metro primarily in the vicinity of the large (design average flow of 5.5 m^3/sec [125 MGD]) West Point discharge. These studies have included sampling of: demersal fishes with otter trawls; pelagic fishes with midwater trawls and echosounders; ichthyoplankton with high-speed plankton nets; and nearshore fishes with beach seines.

Although there were basic similarities in the demersal fish communities at West Point, Alki Point, and Point Pully (control), differences were also noted. In particular, demersal fish abundance was higher at West Point at depths of 70 and 95 m (230 and 312 feet) than at either of the other two locations, possibly due to higher numbers of ratfish (*Hydrolagus colliei*) at West Point. It is conceivable that ratfish are attracted to the area by the sewage discharge. Other differences noted among the three sites (e.g., the replacement of slender sole [*Lyopsetta exilis*] by rex sole [*Glyptocephalus zachirus*] at West Point) may be the result of alterations in the benthic invertebrate community which change the array of available prey items for these demersal fishes.

The catches of pelagic fish species were subject to considerable seasonal variability and a high degree of patchiness, making it difficult to identify spatial trends in the distribution of these fishes which might be affected by the discharge of sewage effluent near West Point. Far more extensive sampling would be required to determine whether pelagic fish distributions were influenced by the West Point discharge.

The limited nature of the ichthyoplankton data (English 1976a; English and Thorne 1977) severely restricts conclusions regarding possible impacts of the West Point discharge on this community. The patterns of seasonal abundance of fish eggs in a broad area surrounding the West Point outfall do not appear qualitatively different from those in the Central Basin of Puget Sound as a whole, but further conclusions regarding possible effects of this discharge on ichthyoplankton are unjustified with the data presently available.

Miller et al. (1977) found that there were differences among West Point, Alki Point, and Point Pully nearshore fish communities in species composition, species richness, abundance, diversity, and in the frequency of occurrence of several fish species. In general, Alki Point and Point Pully were reported to be more similar to one another in terms of these characteristics than to West Point, suggesting possible effects of the sewage discharge at West Point. It is possible, however, that these differences could be attributed to differences in habitat type, since the north shore of West Point sampled by Miller et al. (1977) did not have extensive eelgrass beds, as did Alki Point and Point Pully. Moulton et al. (1974) sampled nearshore fish communities on the south shore of West Point where eelgrass beds do occur, and noted higher values of species diversity and species richness. Hence, it is not clear that the West Point sewage discharge has adversely affected nearshore fish populations.

More limited studies of the ecology of fish communities in the vicinity of sewage outfalls have been conducted in support of 301(h) applications for several smaller Puget Sound municipalities.

Limited quantitative data on the distribution of pelagic fishes near the site of the existing Tacoma North End sewage outfall are available (City of Tacoma 1979a), and similar data are also available for the site of the proposed Tacoma Central sewage outfall off the mouth of the Puyallup River (City of Tacoma 1979b). The former data are so limited that virtually nothing can be deduced about possible impacts on fishes of the relatively small (design flow of 0.44 m^3/sec [10.0 MGD]) Tacoma North End sewage discharge, while the latter data, collected only at the site of a proposed outfall extension and not in the vicinity of the existing effluent discharge, do not bear on an evaluation of effluent-related impacts on fish. Attempts to collect pelagic fishes near the Tacoma Western Slopes sewage outfall using gill nets were thwarted by entanglement of the

nets in the strong currents of the Tacoma Narrows (City of Tacoma 1979c).

Demersal and pelagic fishes were sampled in the vicinities of the Anacortes Main and Skyline sewage outfalls using floating and sinking beach seines, an otter trawl, a purse seine, hook and line, and a spear gun. The data reported are only qualitative, however, limiting examination of effluent-related impacts (City of Anacortes 1979a,b). Diverse fish assemblages were present in the vicinity of each treatment plant outfall, suggesting that the effluent discharges have not adversely affected the species composition of the pelagic and demersal fish communities; but in the absence of quantitative data, it is not possible to ascertain whether the effluent has adversely affected fish abundance.

The 301(h) applications from the town of Steilacoom and from Tacoma's Westside Water District included qualitative observations of fishes by divers in the vicinity of each sewage outfall (Westside Water District 1979; Town of Steilacoom 1979). The very limited qualitative nature of these observations does not permit examination of possible adverse effects of these discharges on the ecology of the resident fish populations.

Effects on Fish Ecology in the Vicinity of Pulp and Paper Mill Discharges. Several field sampling programs have been conducted to ascertain possible effects of the discharge of pulp and paper mill effluents on resident fish populations. The most extensive of these programs (Federal Water Pollution Control Administration [FWPCA] and Washington State Pollution Control Commission [WSPCC] 1967) included detailed studies in the vicinity of pulp and paper mills at Bellingham Bay, Anacortes, Everett, and Port Angeles. Other sampling programs (English 1976b; Moore 1976) examined changes in the resident fish populations of Port Gardner as pollution abatement procedures were implemented at pulp and paper mills in Everett.

The sampling programs in Bellingham Bay, Port Gardner (Everett), and Port Angeles (FWPCA and WSPCC 1967) included studies designed to document the occurrence and migration of juvenile salmon in areas potentially influenced by the discharge of pulp and paper mill effluent. Each of these areas was found to be an important nursery area for juvenile salmon. Knowledge of the distribution of these fishes in each area was then combined with results of toxicity bioassays (to be described below) to assess the potential impact of these discharges on this important resource. In each area, juvenile salmon were found to frequent areas known to be influenced by the pulp and paper mill wastes.

Studies were also conducted in Bellingham Bay and Port Gardner (Everett) to document the distribution and abundance of English sole (*Parophrys vetulus*) eggs in areas potentially influenced by the discharge of pulp and paper mill wastes (FWPCA and WSPCC 1967). In each area, it was found that large numbers

of English sole eggs were spawned in areas polluted by pulp and paper mill wastes, and that they develop in the surface layers where the concentrations of sulfite waste liquor (SWL) were highest. Knowledge of the distribution of these fish eggs in each area was then combined with the results of toxicity bioassays (to be described below) to assess the potential impact of these discharges on the spawning success of the English sole populations.

The fish sampling programs in Bellingham Bay, Port Gardner (Everett), and Port Angeles did not include the collection of demersal fish species which may also be expected to be influenced by the discharge of pulp and paper mill wastes. Studies of juvenile salmon and English sole eggs were not conducted in Guemes Channel near Anacortes, presumably because of the strong currents and significant mixing which occur there.

The studies of Moore (1976) and English (1976b) were designed to document possible beneficial changes in resident fish populations of Port Gardner which might be caused by reductions in pulp mill waste discharges to Everett Harbor. Emphasis was placed on sampling of juvenile salmon and English sole. Although the results were limited to the period 1973-1976, there were indications that there may have been improving trends in such things as larger numbers of chinook (*Oncorhynchus tshawytscha*) and coho (*O. kisutch*) salmon in the East Waterway and along the beaches of Port Gardner, and larger catches of English sole in 1975-1976 relative to 1974-1975. Additional sampling would be necessary to ascertain whether such changes were actually due to pollution abatement procedures implemented at the Everett pulp and paper mills, or whether these changes were simply a result of natural year-to-year variability.

Although studies have not been conducted on the effects of pulp mill effluent on salmon migrations in Puget Sound, correlation between effluent levels and changes in salmon migration patterns have been noted elsewhere (Pearson 1980). Pearson (1980) also noted the occurrence of synergistic reactions between organics in pulp mill effluent and heavy metals from adjacent dischargers. Organics often bonded with heavy metals, thereby providing a ready route for uptake of heavy metals by the biota.

Effects on Fish Ecology in the Vicinity of Diverse Industrial Complexes. Miller et al. (1975, 1977) sampled fish populations at a number of locations in the Duwamish River, a heavily industrialized urban estuary, in 1974-1976, and compared their results with those of a study conducted in this area in 1966-1967 (Salo 1969). Miller et al. (1977) reported that this time interval corresponded with a period of increasingly heavy industrial utilization, although possible changes in the industrial discharges to the river were not discussed. Twenty-nine species of fishes were collected in the Duwamish River, and the only change between 1966-1967 and 1974-1976 in the pattern of dominance by the five most abundant species was the appearance

of longfin smelt (Spirinchus dilatus), which had not been caught in the former collections. Miller et al. (1977) hypothesized that this difference may have been due to spatial and/or seasonal differences in the sampling programs. Pooled annual Shannon-Wiener diversity indices also varied little between 1966-1967 (H'=1.85), 1974 (H'=1.92), and 1975-1976 (H'=2.02), leading Miller et al. (1977) to conclude that these data suggest that the environmental quality of the Duwamish River as measured by ichthyofauna had not changed appreciably over the period represented by these sampling programs.

Malins et al. (1980, 1982a) collected demersal and midwater fishes in otter trawls at various sampling sites in Puget Sound, which included both heavily industrialized areas (Commencement Bay and adjacent waterways; Elliott Bay and the Duwamish River), as well as relatively undeveloped and therefore less polluted areas (e.g., Case Inlet, Port Madison). The objectives of these studies were to characterize the abundance (measured as catch per unit effort [CPUE]), distribution, community characteristics (species diversity, richness, and composition), and biological characteristics (length, weight, and age) of target fish species. English sole (Parophrys vetulus), rock sole (Lepidopsetta bilineata), and Pacific staghorn sculpin (Leptocottus armatus) were chosen as the target species based on their broad distributions, high abundances, and seasonal availability.

Based on total abundances and species composition, richness, and diversity, Malins et al. (1982a) separated the sampling locations into three categories which they considered to represent separate ecological habitats for the demersal and midwater fishes sampled: 1) the estuarine embayments (Elliott and Commencement Bays, and Port Susan), 2) the open bays (Port Madison and Discovery Bay), and 3) the shallow water inlets without major river inputs (Budd, Case, and Sinclair Inlets). Both total abundance and species richness were highest in the estuarine embayments, lowest in the shallow inlets, and intermediate in the open bays. Species diversity was also highest in the estuarine embayments and lower in the inlets.

Malins et al. (1982a) attempted to examine interrelationships between the fish catch rates (CPUE) for the three target species and sediment chemical composition by using Spearman's rank correlation method. They reported that CPUE for some of the target species was found to be negatively correlated with the relative concentrations of certain groups of chemical contaminants (i.e., the fish were more abundant where the concentrations of those chemicals were low, and vice versa). While such correlations are suggestive of cause-and-effect relationships between the fish distributions and the concentrations of chemical contaminants, they are of little value in determining the actual cause of variations in fish abundance. The fish distributions may be ultimately due to some factor unrelated to chemical contaminants but correlated with them; they may be only indirectly related to the concentrations of chemical contaminants (e.g., by the influence of the chemical

contaminants on the distributions of preferred prey items); or the fish distributions may be influenced by complex combinations of chemical contaminants inadequately represented by the groupings of Malins et al. (1982a). Hence, far more information is necessary before it will be possible to determine the relationships (if any) between fish distributions and the discharge of chemical contaminants into these heavily-industrialized estuarine embayments.

Dames and Moore (1981) conducted a field sampling program in Commencement Bay and the adjacent waterways to describe the timing, patterns, and distribution of juvenile salmonids passing through this heavily-industrialized nearshore environment. In addition, Dames and Moore (1981) sampled marine fish in these areas to characterize the seasonality, distribution, and abundance of these populations. The results of both sampling efforts are primarily descriptive in nature and serve to define baseline conditions in these areas. The data were not analyzed in such a way that it is possible to examine potential relationships between the distributions of these fishes and presence of chemical contaminants derived from any of the diverse industries occurring in this area. Dames and Moore (1981) also summarized available information on the occurrence of adult salmonids in the Commencement Bay study area, but no field studies of these fishes were conducted.

Chew and Becker recently sampled demersal fish and benthic invertebrate communities at 12 locations in Puget Sound (Becker pers. comm.). Their objectives were to characterize and compare demersal fish communities in areas influenced by organic enrichment, and to provide explanations for any observed differences in community characteristics. They hypothesized that organic enrichment influences demersal fish communities indirectly through effects on benthic invertebrate communities, the primary food source of the fishes. They attempted to evaluate this indirect influence of organic enrichment on fish communities by: 1) testing for differences in community characteristics and species abundances between enriched and unenriched (control) sites, 2) comparing the effects of large-scale, multi-source enrichment with the effects of highly localized, point source enrichment, and 3) determining the extent to which observed station patterns could be generalized across different embayments. Although not specifically designed to examine the direct effects of pollution, this study did include sampling of fishes and benthic invertebrates in industrialized portions of Commencement Bay, near the Denny Way combined sewer overflow in Elliott Bay, and near the harbor in Bremerton on Sinclair Inlet. Important differences were found in the distribution and abundance of demersal fishes that appear to be correlated with depth of habitat, degree of organic enrichment, time of day, and season (Becker pers. comm.). Analyses of the fish stomach contents and of the benthic invertebrate communities have not been completed at this time, although the results, when available, should provide further clues regarding the factors

important in structuring demersal fish communities of Puget Sound. While not directly related to pollutant effects, this study may provide important evidence of effects which could occur in demersal fish communities if pollutants were to alter the benthic invertebrate communities.

Effects on Fish Ecology in the Vicinity of Dredge Spoil Disposal Sites. During 1976, contaminated dredge spoils were removed from the Duwamish River and disposed of in Elliott Bay. Hughes et al. (1978) sampled demersal fishes at the disposal site and at two reference sites in Elliott Bay before, during, and at several intervals after disposal of these dredge spoils. Although they concluded that there was no lasting effect of the dredged material disposal on fish species composition and abundance, Hughes et al. (1978) cautioned that the data were difficult to interpret. Statistically significant differences in both composition and abundance of several species at the three sampling sites might have been caused by natural population fluctuations due to seasonal migrations for spawning, feeding, etc. In addition, interpretation of the data was further complicated by the fact that the three test sites were not comparable with respect to bottom sediments, proximity to a source of fresh water, and indigenous species present. Finally, the time of disposal coincided with the flood stage of the Duwamish River, when large volumes of sediment were being carried naturally into Elliott Bay. Hence, results of this study may not necessarily have direct implications on the possible effects of the disposal of dredge materials in other areas of Puget Sound.

Lethal Toxicity Bioassays

Fishes have been used in a variety of bioassays to attempt to assess the toxicity of various contaminants to organisms in the receiving water environments of Puget Sound. Studies have included *in situ* bioassays with fish confined to cages and held for varying lengths of time in the receiving water environment, simulated *in situ* bioassays with the fish exposed in aquaria to flowing seawater pumped from the receiving water environment and laboratory bioassays with fish exposed either to contaminated sediments or to various dilutions of municipal sewage effluents. These bioassays have been used to assess the toxicity of wastes from pulp and paper mill discharges, as well as the effluents from municipal sewage treatment plants. They have also been used to examine possible toxic effects on fish of contaminated sediments from industrial estuaries, and the toxicity of suspended dredge spoils.

Both acute and chronic laboratory bioassays have been conducted by Stober et al. (1977) using various dilutions of West Point sewage treatment plant effluent to assess its toxicity to three fish species: English sole (*Parophrys vetulus*), shiner perch (*Cymatogaster aggregata*), and Pacific staghorn

sculpin (Leptocottus armatus). The first two species were found to be the most sensitive, and therefore the bioassays concentrated on these species. Various experimental manipulations were employed to examine the effect of filtration, dechlorination, and dechlorination plus removal of ammonia on the toxicity of the effluent. All three procedures were demonstrated to result in reduced toxicity of the effluent to these two fish species. The results were used to calculate safety factors (the quotient of the concentration of the effluent after initial dilution divided by the LC_{50} concentration for that effluent [the LC_{50} concentration is that concentration lethal to 50 percent of the test animals]).

Slug discharges of potentially toxic substances such as trace metals may drastically alter the toxicity of the effluent, however, and thereby decrease the margin of safety if these safety factors are applied to the effluent discharge. Abnormally high mortality was observed in two 96-hour bioassays, for instance, which resulted in LC_{50} values of less than 10 percent effluent (on a volume/volume basis). While the exact toxic component remains unknown, circumstantial evidence points to trace metals since concurrent chemical analyses indicated that these high mortalities coincided with unusually high effluent concentrations of mercury in one case, and of cadmium and copper in the other case.

Chronic bioassays were also used by Stober et al. (1977) to assess the possible bioaccumulation of trace metals in these fish species. The results of these analyses are described below under bioaccumulation.

FWPCA and WSPCC (1967) utilized both in situ bioassays and simulated in situ bioassays to assess the toxicity of the waters of Bellingham Bay, Port Gardner (Everett), and Port Angeles to juvenile salmon. Each of these areas received the wastes from pulp and paper mills. For the in situ bioassays, fry were held in live boxes at each of a number of stations in the receiving water bodies. The duration of the exposures was either 4 or 24 hours, during which time the condition of the fish was checked periodically. The numbers of fish which had died at each location were used as an indicator of the toxicity of the receiving water at that location. For the simulated in situ bioassays, water was pumped from the receiving water body into flow-through test chambers. Salmon fry were placed in these test chambers and observers were able to monitor the behavior of these fish and to take frequent samples for water quality analyses. In this manner, waters eliciting an adverse response in the fish were tested in order to ascertain the causes of the adverse responses observed.

In Bellingham Bay, the waters of the inner harbor in the vicinity of a sulfite pulp and board mill were found to cause frequent, high-percentage kills of the test fish. Along the shore north of this area, no kills were observed, while in the

area south of the mill, kills occurred but these were usually low-percentage kills with more of the fish surviving than dying. The frequent, high-percentage kills were found to be associated with high concentrations of SWL, low concentrations of DO, reduced pH, and variable concentrations of ammonia, i.e., conditions indicative of water quality degradation by mill wastes. The area having no kills had very low SWL concentrations, DO near saturation, normal pH, and low concentrations of ammonia. As might be expected the area having low-percentage kills evidenced concentrations of SWL, DO, and pH at levels intermediate of the two extremes. It is interesting to note that observations of the distressed and dying fish revealed that all of the dead salmon fry sank (which implies that natural fish kills in this area might go unnoticed by shipboard or shore-based observers), and that before dying, the fish exhibited disoriented, erratic swimming behavior with no avoidance response (suggesting that fish exposed to these wastes may fall victim to predators before actually succumbing to the toxic effects of the wastes).

In Port Gardner (Everett Harbor), frequent, high-percentage kills were reported from the vicinities of two sulfite pulp and paper mills; infrequent, low-percentage kills were reported from other areas inside the harbor; and zero mortality was observed in all but one of the tests outside the harbor. The mortalities in this area were usually associated with periods when low tides allowed the surface waters to be affected by hydrogen sulfide (H_2S) released from sludge on the bottom, although on a few occasions, the mortalities were apparently caused by high residual chlorine concentrations resulting from the discharge from one of the two mills.

In Port Angeles Harbor, frequent, high-percentage kills were also observed in the vicinities of three pulp, paper, and board mills. Here the principal cause of the observed mortalities also appeared to be high concentrations of total sulfides, although certain kills were also associated with low DO concentrations, high SWL concentrations, and low pH values. Hence, the discharges from these mills were also implicated in causing the observed mortalities.

FWPCA and WSPCC (1967) also utilized English sole eggs in laboratory bioassays designed to assess the toxicity of SWL. For these bioassays, eggs and sperm were stripped from ripe English sole collected in unpolluted areas of Puget Sound. The eggs were fertilized and then exposed to varying concentrations of a composite sample of SWL from a paper mill in Anacortes, as well as to control samples of unpolluted seawater. The seven test solutions used contained SWL in a logarithmic series of concentrations: 5.6, 13.5, 32, 75, 180, 420, and 1,000 ppm. These samples were incubated until 24 hours after larvae had appeared in the control samples. The eggs and larvae were then anesthetized, fixed in formalin, and examined under a dissecting microscope. Counts were then made of the numbers of dead eggs

with no apparent embryonic development, developing eggs with no indication of hatching, transitional larvae (those still having ventral flexure or parts of the shell adhering), normal larvae, and abnormal larvae.

Sulfite waste liquor was found to be severely damaging to developing English sole eggs, even when dilute. There were apparent increases (relative to the controls) in the numbers of dead and unhatched eggs at SWL concentrations of 13.5 ppm, and increases in the numbers of abnormal larvae even at the lowest concentration tested (5.6 ppm). Higher concentrations resulted in increased severity of the effects and significant retardations in development, suggesting that little survival would occur. The bioassays demonstrated that SWL is an effective agent in disrupting the normal metabolic processes of developing English sole eggs. The greatest change in response occurred between 5.6 and 13.5 ppm, suggesting a critical threshold of about 10 ppm. Measurements of SWL concentrations in the vicinity of the pulp and paper mills at Bellingham, Anacortes, Everett, and Port Angeles were often found to be in excess of 10 ppm, and hence it is likely that these wastes were adversely affecting English sole eggs spawned in these areas.

Moore (1976) also used salmon fry in live box bioassays to assess the toxicity of the waters in Everett Harbor during a period when improvements were being made in the quality of the effluents discharged from the mills there. While he noted a slight decrease in the mortalities which may have been associated with the reduction in waste load, significant mortalities still occurred in areas near the mills. The cause of these mortalities was apparently H_2S from the sludge deposits on the bottom, however, which would not necessarily reflect the quality or quantity of the mills' waste load at the time of the bioassays. The results of further live box bioassays conducted for several years after initiation of pollution abatement measures have not yet been released.

McCain et al. (1982) conducted two laboratory bioassays in which English sole were maintained for 2-3 months in aquaria containing either test sediments from an area known to be contaminated with a variety of industrial chemicals (Duwamish Waterway) or reference sediments from a presumed unpolluted site (Snohomish River in bioassay 1 or Port Madison in bioassay 2). While the purpose of these experiments was to compare pathological characteristics of fish exposed to these treatments, relevant data on the lethal toxicity of these sediments to the fish were also provided. In the first bioassay, the mortality in the test group (Duwamish Waterway sediment: 16 percent; 16 of 100 fish) was lower than the mortality in the reference group (Snohomish River sediment: 27 percent; 27 of 100 fish). In the second bioassay, the mortality in the test group (Duwamish Waterway sediment: 54 percent; 19 of 35 fish) was higher than the mortality in the reference group (Port Madison sediment: 38 percent; 12 of 32 fish). However, neither difference was

statistically significant. While these results would appear to imply that the Duwamish Waterway sediments are not unusually toxic to English sole, consideration must be given to the cause of the high mortalities in the reference samples. McCain et al. (1982) contend that the reference sediments may have been poorly selected since the Port Madison sediment was shown to have a higher concentration of chlorinated butadienes than did the Duwamish Waterway sediment, and there were indications that the Snohomish River sediment contained high concentrations of pesticides and PCBs. They suggest that future sediment exposure experiments may require that reference sediments be obtained from outside Puget Sound.

Malins et al. (1982b) tested effects of low (15-150 ppb) waterborne hydrocarbons on smelt, flatfish, and salmon. Less than 10 percent of the smelt eggs hatched, and of those that did, only 10 percent survived. Flatfish embryos exposed to 80 ppb developed normally; those exposed to 130 ppb died or were grossly abnormal. At concentrations of 150-500 ppb, exposure during embryo and alevin development increased mortality 400 percent; exposure to either embryos or alevins alone increased mortality by 100-150 percent. Exposure of adult salmon to 1-2 ppm aromatic hydrocarbons caused a delay in returning salmon migration; 2-3 ppm inhibited upstream migration. Exposure to 40 ppm freshwater-accommodated crude oil did not alter their homing capability or rate of return. Other experiments produced less effect; juvenile flatfish did not consisently avoid oil-sediment mixtures containing 8,000-10,000 ppm total hydrocarbons, and maturing trout fed 1,000 ppm for 7 months did not show significant changes in hatching success.

Westley et al. (1975) utilized similar live box bioassays with salmon fry to test the water quality which resulted from dredging activities in Budd Inlet. Experiments were conducted to assess the effects of both suction dredging and clamshell dredging, as well as the effects of two methods of disposal (barge and pipeline). Interpretation of the results was somewhat difficult because relatively high mortalities occurred in the control boxes as well as in the experimental boxes. It is possible that a massive red tide and warmer water temperatures were responsible for these mortalities. The study concluded that the water quality resulting from the dredging was not highly toxic because a number of fish survived in each test, and that it was not possible to determine which dredging method had the lesser potential for adverse effects on these fish. However, the results of this study are not directly applicable to dredging activities in other areas where the composition of the sediments is markedly different.

Bioaccumulation

A number of investigators have analyzed the concentrations of trace metals, PCBs, pesticides, and other organic chemical

contaminants in fishes from various locations throughout Puget Sound. In at least a few of these studies, attempts have been made to examine correlations between the tissue concentrations of these contaminants and the distribution of known point sources of these substances.

Trace Metals. Analyses of the tissue concentrations of a number of trace metals have been conducted on fishes from a number of locations in Puget Sound. While all of the metals are naturally-occurring elements, there is concern that metals introduced to the Sound by the activities of man may have increased the background concentrations of these metals in either the water or in the sediments. This may cause an increase in tissue concentrations of these metals in the biota of the Sound. Hence, a number of these studies have examined the concentration of metals in fishes near known sources of metallic wastes. Naturally, one would expect that if bioaccumulation of these metals is occurring, effects would be more pronounced in demersal fishes, which tend to be more permanent residents in a given area, than in pelagic fishes, which are only transient residents. Consequently, emphasis has been placed in most of these studies on measuring the tissue metal concentrations in demersal fish species.

Before reviewing the existing information, it should be noted that a major obstacle occurs in interpreting the meaning of these data. The significance of abnormally high concentrations of certain heavy metals in certain fish is not readily apparent since it is not known whether these elevated concentrations have any adverse effect on the fish. In addition, the consequences of these elevated tissue metal concentrations on persons possibly eating these fish are also largely unknown. An FDA action level has been identified only for mercury, and there are no restrictions on the ingestion of fishes containing high concentrations of any of the other metals.

Crecelius (1974) measured the concentrations of arsenic and antimony in the muscle tissues of several species of sole collected in Carr Inlet, near Fox Island, in Quartermaster Harbor (Vashon Island), and over the slag pile of the ASARCO smelter in Tacoma. Quartermaster Harbor is known to receive atmospheric fallout of smelter stack dust which is rich in both arsenic and antimony. The smelter slag is also known to contain high concentrations of these metals. In addition, Crecelius (1974) measured the concentrations of arsenic and antimony in ratfish (*Hydrolagus colliei*) collected over the smelter slag pile and near Fox Island. The highest concentration of arsenic found among all of these fish tissues was 41 ppm dry weight in the muscle of the ratfish from Fox Island. Concentrations of arsenic in the ratfish and sole from the vicinity of the slag pile were also moderately high (29-31 ppm dry weight), but the total range of arsenic concentrations measured in all of the fish was small (8.5-41 ppm dry weight). The lowest concentrations were found in sole from Quartermaster Harbor, where the

sediments are known to have higher than normal concentrations of arsenic. Antimony was only present in very low concentrations; it was found near or below the limit of detection in the fish from all locations except the vicinity of the slag pile, where it was found in the ratfish and sole at concentrations of 0.8 and 0.9 ppm dry weight, respectively. Crecelius (1974) concluded that there was no consistent pattern of accumulation of these two metals in the fish examined.

Cummins et al. (1976) analyzed the concentrations of 12 metals in the muscle tissue of several sculpins and sole collected in Liberty Bay, as well as the concentrations of those same metals in a sculpin from Hood Canal, and in a sole from Clam Bay, both of which were intended to serve as controls. Despite the fact that Liberty Bay had received for many years the untreated metallic electroplating wastes from the Keyport Navy Torpedo Station, there were no obvious elevations in the tissue metal concentrations among these fishes. The only major difference among the fishes analyzed by Cummins et al. (1976) was the finding of a relatively high concentration of arsenic (14 ppm wet weight) in the sole from Clam Bay, the intended control. Concentrations of arsenic in the muscle tissue of the other fishes ranged between 0.10-0.70 ppm wet weight. Cummins et al. (1976) reported, however, that the high concentration of arsenic in the Clam Bay sole corresponded with the range of arsenic concentrations (5.4-13.8 ppm) found in muscle tissues of unspecified flatfishes from Colvos Passage and Commencement Bay by Huntamer and Schell (1974). Cummins et al. (1976) speculated that the higher concentrations of arsenic in these fishes may have been related to their relative proximity to the ASARCO smelter in Tacoma, or to other local sources of arsenic, although they cautioned that further studies were necessary. It should be noted, however, that these concentrations are low relative to those found by Crecelius (1974) and discussed above.

Sherwood and McCain (1976) measured the concentrations of 10 cations and trace metals in muscle and kidney tissues of starry flounders (*Platichthys stellatus*) collected in the Duwamish and Nisqually River estuaries. There were no notable differences in metal concentrations between the fish from the two areas, although the former is a heavily-industrialized urban estuary, and the latter is relatively free of industrial contaminants. It should be noted, however, that their sample sizes were quite small (only nine fish are examined) and further studies would be required to verify the conclusion that metals were apparently not accumulated to abnormal levels by the starry flounder of the Duwamish River estuary.

One of the more extensive studies of trace metals in the tissues of fishes from Puget Sound was conducted for Metro. This study, the results of which are reported by both Olsen and Schell (1977) and Schell et al. (1977), included the analysis of 12 trace metals in the muscle tissues of English sole and Dover

sole collected near Metro's West Point sewage outfall and in a reference area in Hood Canal. In addition, tissue samples were collected from the viscera, muscle, skin, bone, and liver of 14 species of fishes from various locations throughout the Sound. These tissues were analyzed for copper, cadmium, and lead content. The same tissues were also sampled from English sole collected from West Point, Hood Canal, Carkeek Park (the site of a smaller sewage discharge), and the Duwamish River, and analyzed for copper, cadmium, lead, and selenium content.

In the absence of replicate samples and/or any statistical analysis of their data, interpretation of the results of Olsen and Schell (1977) and Schell et al. (1977) is subject to a degree of uncertainty. Since the data for the 14 species of fishes are not separated by area of collection, there can be no analysis of spatial variations in the concentrations of trace metals in their tissues, which might be correlated with known sources of metal contamination, such as the West Point discharge or the Duwamish River. Among the Dover sole and English sole, for which the data were separated by area of collection, there were apparent differences in tissue metal concentrations which might be interpreted as possible effects of increased inputs of these metals. Lead concentrations in the muscle tissue of these species near the West Point outfall were approximately 3 ppm dry weight, while those from Hood Canal were below the limit of detection. In English sole, the concentrations of cadmium in the bone samples and of copper in the liver were higher in fish collected near the outfall than in those from Hood Canal. While such differences in concentrations are suggestive of possible outfall-related effects, much more extensive sampling would be required to establish the statistical significance of these differences.

Malins et al. (1980) reported the concentrations of 16 metals in the livers of English sole and rock sole from various locations in central and southern Puget Sound, including two heavily industrialized areas: Elliott Bay-Duwamish River and Commencement Bay Waterways. There were no apparent differences in the concentrations of these metals which might be associated with proximity to known sources of the metals. Once again, however, the samples were unreplicated, so the significance of the lack of apparent differences is unknown.

Further analyses of metal concentrations in fish tissues were conducted by Malins et al. (1982a). English sole were collected from the Seattle waterfront, the Duwamish River, the Hylebos Waterway of Commencement Bay, and in Port Susan. King salmon (*Oncorhynchus tshawytscha*) and Pacific cod (*Gadus macrocephalus*) were collected from Commencement Bay, Point Jefferson (near Port Madison), and Elliott Bay. The skeletal muscle of these fishes was analyzed for the concentrations of eight metals. Malins et al. (1982a) concluded that only arsenic was present in moderate to high concentrations in the muscle of cod (ca. 2.7 ppm wet weight) and salmon (ca. 6.0 ppm wet

weight). There was no apparent relationship between the concentrations of arsenic and the proximity of the fish to known sources of pollutants. Even the cod from Point Jefferson had a relatively high concentration of arsenic in its muscle tissue. Although not discussed by Malins et al. (1982a), unpublished tabular data made available for this review revealed that both chromium and zinc were also present in moderate to high concentrations (1.1-4.7 ppm wet weight) in the muscle tissues of the salmon and cod, but again there was no geographic pattern correlated with known pollutant sources. Concentrations of mercury in these fishes were far below the available FDA action level. Considering the small numbers of fishes analyzed (8 English sole, 11 salmon, 7 cod), no conclusive interpretations can be derived from these data. Malins et al. (1982a) noted that in light of the known toxic and carcinogenic properties of arsenic, further studies should be conducted of the concentrations of this metal in the edible tissues of Puget Sound organisms.

Copper rockfish (Sebastes caurinus) and pile perch (Rhacochilus vacca) were collected during a WDOE Class II inspection of the ASARCO copper smelter in Tacoma in 1978 (WDOE 1979). The skeletal muscle, gills, liver, and gut contents of these fish were analyzed for the concentrations of eight metals to ascertain whether assimilation of these metals discharged by ASARCO was occurring among animals inhabiting the slag fill and piling habitat adjacent to the smelter. Zinc was present in the highest concentrations (9-80 ppm wet weight), but arsenic was present in only low concentrations (0.4-1.8 ppm wet weight). The latter fact is surprising considering the high concentration of arsenic known to be present in the slag. It was not possible to demonstrate whether significant bioaccumulation of any of these metals was occurring since samples of these fish species were not collected from a reference or control area.

During a second WDOE Class II inspection of the ASARCO smelter (WDOE 1981), blue sea perch (Taeniotoca lateralis) and copper rockfish were collected in the vicinity of one of ASARCO's outfalls, as well as near Hartstene Island in Southern Puget Sound. The latter area was to serve as a control. The skeletal muscle, gills, liver, and gut contents of these fish were analyzed for the concentrations of nine metals. Copper, lead, and zinc were found to have the highest concentrations in the fish from the vicinity of the ASARCO outfall when compared with concentrations in the fish from near Hartstene Island. While these findings are suggestive of possible effects related to the discharge of metallic wastes by ASARCO, it should be emphasized that the number of fish examined was small (a total of 6 blue sea perch and 6 copper rockfish), and therefore the statistical significance of the observed differences is unknown.

Teeny and Hall (1977) collected English sole at several sites in Elliott Bay before and at several intervals after the disposal of contaminated dredge spoils from the Duwamish River. These fish (minus their stomach contents) were analyzed for

their content of mercury and chromium in order to examine the possibility of accumulation of these metals from the dredge spoils. The results indicated that the concentrations of mercury and chromium in these fish were low (less than 0.1 ppm wet weight for mercury and 0.91 ppm wet weight for chromium) and showed no apparent effect of the disposal operation. Caution is advised in concluding from this study that such bioaccumulation did not occur, however, since there can be no guarantee that the fish caught near the disposal area at the end of the sampling period had resided in that area long enough for bioaccumulation to occur.

McCain et al. (1982) analyzed the concentrations of cadmium, chromium, copper, lead, and zinc in English sole collected from the Duwamish Waterway, the Lake Washington Ship Canal, and McAllister Creek (a reference area in Southern Puget Sound). They found no correspondence between the tissue concentrations of these metals and the concentrations of these metals in the sediments where the fish were caught. They suggested that this lack of correspondence might be due to varying degrees of bioavailability of these metals, since the concentrations of the sediment-associated metals extracted with a weak acid may not necessarily reflect the concentrations of metals which are bioavailable to the fish.

Gahler et al. (1982) analyzed metal concentrations in edible muscle tissue of several fish species from popular sport fishing areas in Commencement Bay and Discovery Bay (a reference area). Bottomfishes (e.g., English sole, starry flounder) from the Pt. Defiance Dock had considerably higher total metal concentrations ($\bar{x}$ = 27.6 mg/wet kg) than bottomfishes from Hylebos Waterway, City Waterway, Old Town Dock, and Discovery Bay ($\bar{x}$ = 9.4-12.3 mg/wet kg). Much of the elevated total metal levels in Pt. Defiance Dock bottomfishes resulted from higher concentrations of arsenic in English and rock sole when compared to the other samples. Total metal concentrations in "mixed fishes" (e.g., sculpins, greenlings, and rockfishes) and off-bottom fishes (e.g., hake, cod, and pollock) were relatively consistent among the five sampling areas. Tissue mercury concentrations were well below FDA Action Levels in all species sampled.

Chronic bioassays were conducted by Stober et al. (1977) to examine the toxicity of West Point sewage effluent to English sole and shiner perch (*Cymatogaster aggregata*). After 8-weeks' exposure to various dilutions of the effluent, the fishes were analyzed for their zinc and copper content. No consistent change was found in whole body zinc and copper concentrations with exposure to increasing concentrations of effluent, suggesting that there was no appreciable accumulation of these metals from this source by the fishes.

Polychlorinated Biphenyls (PCBs). PCBs are anthropogenic pollutants of considerable importance due to their slow rates of

chemical and biological degradation, their capacity for bioaccumulation, and their toxicity. While PCBs are no longer used in this country, the ubiquitous distribution in the environment and their persistence, especially in contaminated sediments, ensure that they will continue to be a contaminant of some concern for the foreseeable future. Consequently, there have been a number of studies of the concentrations of PCBs in fishes of Puget Sound and adjacent waters.

Sherwood and McCain (1976) measured the concentrations of total PCBs in muscle, liver, and brain tissues of starry flounders collected in the Duwamish and Nisqually River estuaries. While the number of fish examined was small (a total of only nine fish from the two areas), it is notable that the concentrations of total PCBs were higher in all three tissues among fish collected in the Duwamish River when compared with the corresponding tissues in fish from the Nisqually River. The difference was especially pronounced in the liver concentrations; in the livers of fish with moderate to severe fin erosion from the Duwamish River, the total PCB concentration was 18.8 ppm wet weight, while in the livers of fish with no apparent fin erosion, the total PCB concentration was only 0.53 ppm wet weight in fish from the Nisqually River and 11.9 ppm wet weight in fish from the Duwamish River. These results suggest that fish inhabiting areas known to be contaminated with PCBs (i.e., the Duwamish River estuary) are more likely to have a higher body burden of PCBs than fish living in relatively uncontaminated, nonindustrial areas, but the relationship between body burden in the liver and occurrence of fin erosion is not clear.

Mowrer et al. (1977) collected two species of sculpins at 18 locations throughout south and central Puget Sound and analyzed the concentrations of PCBs in their tissues (type unspecified). The sampling locations included urban estuaries (Duwamish River, Commencement Bay, and Sinclair Inlet), as well as a number of more pristine, less polluted sites. The highest concentrations of total PCBs were found in the sculpins collected in the three urban estuaries. In these areas, the concentrations ranged between 160-840 ppm wet weight, whereas the concentrations in sculpins from less developed portions of Southern Puget Sound ranged between 21-66 ppm wet weight. Sediment samples collected at the same time as the sculpins revealed a similar distribution of PCBs; the highest sediment PCB concentrations were found at the same locations having fish with the highest PCB concentrations. This suggests that demersal fishes exposed to PCB-contaminated sediments may accumulate higher levels of PCBs in their tissues than do fishes exposed to uncontaminated sediments.

Stout and Lewis (1977) collected English sole at several sites in Elliott Bay before and at several intervals after the disposal of contaminated dredge spoils from the Duwamish River. These fish (minus their stomach contents) were analyzed for

their PCB content in order to examine the possibility of accumulation of PCBs from the dredge spoils. Before the disposal operation, the English sole collected in this area had a relatively high PCB content (average concentration for three fish = 2.28 ppm wet weight). Inexplicably, the average concentration of PCBs decreased after disposal of the contaminated sediments (average concentrations for three fish were 0.65 and 0.87 ppm wet weight for fish collected 2 weeks and 1 month, respectively, after the disposal operation). English sole were then unavailable at these sampling locations until 9 months after the disposal operation, when a single specimen was determined to have a PCB concentration of 5.90 ppm wet weight. Stout and Lewis (1977) suggest that it appears that English sole migrated out of the area during the middle of this experiment, and therefore the sole collected 9 months after disposal may not have been a permanent resident of the area during this period. While the results do not clearly demonstrate whether any accumulation of PCBs from the sediments may have occurred in these English sole, they do point out the potential complications arising from attempts to follow changes in chemical concentrations in a single population of organisms sampled at various intervals over an extended period of time. Among mobile organisms, such as English sole, there can be no guarantee that an individual has been a permanent resident of the area under study for any extended period of time.

Chronic bioassays were conducted by Stober et al. (1977) to examine the toxicity of West Point sewage effluent to English sole. After 8-weeks' exposure to various dilutions of the effluent, the fishes were analyzed for their PCB content. In all dilutions, as well as in the seawater control, the fish lost PCB relative to the concentration in a similar fish analyzed at the start of the experiments. Stober et al. (1977) noted that the PCB in the fish tissue was the 1260 form, while that in the effluent was primarily the 1254 form. This suggests that these fish did not bioaccumulate PCB from the effluent, perhaps because it was not in a chemical state readily assimilated by the fish. The apparent depuration of PCB in the test fish could, according to Stober et al. (1977), be attributed to the replacement of a natural, PCB-contaminated food source by a relatively uncontaminated food source during the course of the bioassays.

McCain et al. (1982) analyzed the PCB concentrations in the livers of English sole collected in the Duwamish Waterway, the Lake Washington Ship Canal, and McAllister Creek, a reference estuary in Southern Puget Sound. They found that the concentrations of PCBs in the livers of these fish reflected the concentrations of PCBs in the sediments where the fish were collected. In the Duwamish Waterway, for instance, where the sediments are known to be contaminated with PCBs, the concentrations of PCBs in the fish livers ranged between 17-171 ppm dry weight. The concentration of PCBs in a composite sample of English sole livers from McAllister Creek (where the sediment concentrations

of PCBs were low) was only 0.5 ppm dry weight. These results suggest that English sole may accumulate PCBs from contaminated sediments when the fish are residents in areas having such sediments.

Malins et al. (1980) reported the concentrations of total PCBs in the livers of English sole and rock sole from various locations in the Central Basin of Puget Sound and Southern Puget Sound, including two heavily industrialized areas: Elliott Bay-Duwamish River and Commencement Bay Waterways. The highest total PCB concentrations in the livers of these fishes were found in specimens collected in the Duwamish Waterway, in the Hylebos Waterway, at Brown's Point (on the north shore of Commencement Bay), in Elliott Bay, and in Sinclair Inlet. Fish from control areas, such as Case Inlet and Port Madison, had considerably lower concentrations of total PCBs in their livers. Malins et al. (1980) also demonstrated that the concentration of total PCBs was higher in the livers of English sole collected from Commencement Bay than in the muscle tissues of those same fish. Malins et al. (1980) provided limited information on the concentrations of individual classes of PCBs (e.g., dichlorobiphenyls, trichlorobiphenyls, nonachlorobiphenyls) in the livers of English sole, rock sole, Pacific staghorn sculpin (Leptocottus armatus), and quillback rockfish (Sebastes maliger), although the geographic coverage was not as comprehensive (i.e., specimens of the latter two species were only examined from Elliott Bay and Commencement Bay). In the absence of analyses of specimens of the latter two species from control areas, nothing can be said regarding the relative concentrations of these substances in their livers.

Further analyses of PCB concentrations in fish tissues were conducted by Malins et al. (1982a). English sole were collected from the Duwamish River, the Hylebos Waterway off Commencement Bay, and in Port Susan. Chinook salmon and Pacific cod were collected from Commencement Bay, Point Jefferson (near Port Madison), and Elliott Bay. Both the skeletal muscle and the livers of these fishes were analyzed for the concentrations of total PCBs. The concentrations of total PCBs were highest in the livers of English sole from the Duwamish River and Commencement Bay, and were apparently elevated over those in the livers of sole from Port Susan (the reference area). Concentrations of total PCBs in the muscle tissues of English sole from the Duwamish River and Commencement Bay were lower than the liver concentrations, but analyses were not performed on sole skeletal muscle from Port Susan. The concentration of PCBs in the livers of cod may have been slightly higher in Duwamish River and Commencement Bay specimens than in those from Port Susan, but the number of fish examined (a total of eight) renders such a conclusion tentative. There were no apparent differences in the concentrations of PCBs in the livers or skeletal muscle of the salmon that might be related to the area of capture.

Similar results were obtained by Gahler et al. (1982) who reported elevated PCB levels in muscle tissue of English sole from Commencement Bay. The highest tissue concentrations of PCBs occurred in demersal or semidemersal fishes (e.g., sculpin, greenlings) from the Hylebos Waterway, although the maximum values (1.12 mg/wet kg) were well below the FDA Action Level of 5 mg/wet kg. PCB concentrations in "off-bottom" fishes such as cod and hake were consistently low (* <0.09 mg/wet kg) in the Commencement Bay samples and in the Discovery Bay reference samples.

These results suggest that demersal fish species (such as the English sole), may accumulate PCBs in their tissues when they are exposed to PCB-contaminated sediments, but that the concentrations of PCBs in wide-ranging pelagic species such as salmon apparently bear no relationship to the sediment concentrations of PCBs in the area of capture. Similar results have been obtained in studies done elsewhere, e.g., Courtney and Langston (1980) demonstrated uptake of PCBs from sediments by turbot over a 15-day exposure period.

Other Organic Compounds. Various studies have attempted to analyze the concentrations of anthropogenic organic compounds other than PCBs in the tissues of fishes from a number of locations in Puget Sound. These compounds include pesticides, CBDs, PAHs, and other organic compounds known to be discharged to the Sound in industrial and municipal effluents. There is concern that certain of these compounds may be accumulated in the tissues of fish to the extent that they either have adverse effects on the fish or represent a health hazard to humans eating the fish.

Sherwood and McCain (1976) measured the concentrations of p,p'-DDE (a pesticide derivative) in muscle, liver, and brain tissues of starry flounder collected in the Duwamish and Nisqually River estuaries. The concentrations of p,p'-DDE were low in all of these tissues, although there was a suggestion of higher concentrations in the livers of fish from the Duwamish River (0.213 ppm wet weight) than in those from the Nisqually River (0.035 ppm wet weight). Further studies would be required to verify that these concentrations were in fact significantly different, and to ascertain whether there were differences in the concentrations in the other tissues.

In addition to the aforementioned analyses of PCBs in English sole during chronic bioassays of West Point sewage effluent, Stober et al. (1977) also measured the concentrations of total chlorinated hydrocarbons in these fish. After 8-weeks' exposure to the effluent, the fish in all dilutions of the effluent, as well as those in the seawater control, lost chlorinated hydrocarbons relative to the concentration in a similar fish analyzed at the start of the experiments. The results suggest that these fish did not bioaccumulate chlorinated hydrocarbons from the effluent, perhaps because these compounds, like

the PCBs, were not in a chemical state readily assimilated by the fish. The apparent depuration of chlorinated hydrocarbons in the test fish could, as in the case of PCBs, be due to the replacement of a natural, contaminated food source by a relatively uncontaminated food source during the course of the bioassays.

Roubal et al. (1978) examined the uptake of low molecular weight aromatic hydrocarbons in coho salmon (Oncorhynchus kisutch) and starry flounder (Platichthys stellatus) exposed in flowing seawater aquaria with approximately 0.9 ppm of a water-soluble fraction of crude oil. Both species were found to accumulate a complex spectrum of low molecular weight aromatic hydrocarbons, although bioconcentration factors were higher for the flounder than for the salmon. In general, the alkylated aromatic hydrocarbons were accumulated to a greater degree than the unsubstituted derivatives. Whereas the salmon were able to purge their tissues of the accumulated hydrocarbons within 2 weeks when transferred to clean seawater, the flounder still retained substantial concentrations of substituted napthalenes and benzenes. It appears that the presence of aromatic hydrocarbons may be responsible for the induction of enzyme systems responsible for the metabolism of these compounds (Roubal et al. 1978).

In addition to the analyses for metals and PCBs described earlier, Malins et al. (1980) measured the concentrations of petroleum hydrocarbons, chlorinated pesticides, and other chlorinated hydrocarbons in the livers of English and rock sole, Pacific staghorn sculpins, quillback rockfish, and Pacific tomcod. Due to their widespread distribution and their higher prevalence of pathological abnormalities, the results for English sole and rock sole were discussed in greatest detail. Whereas the concentrations of individual polynuclear aromatic hydrocarbons in the livers of these species caught in the nonurban areas of Puget Sound were either below or close to the detectable limits of these compounds, the livers of fishes from Elliott Bay and Commencement Bay generally had higher levels of these compounds. For the CBDs, the only area where the concentrations in the fish livers were consistently high was the Hylebos Waterway of Commencement Bay. Both the chlorinated hydrocarbon pesticides and hexachlorobenzene were present in highest concentrations in the livers of fishes from the Duwamish Waterway, the Seattle waterfront, and the Hylebos Waterway. The pesticides were present at intermediate levels in fish from Sinclair Inlet, Brown's Point, Southwest Commencement Bay, and West Point, and at low levels in outer Elliott Bay, Port Madison, and Case and Budd Inlets. Malins et al. (1980) also demonstrated that the concentrations of both hexachlorobenzene and hexachlorobutadiene were higher in the livers of English sole collected from Commencement Bay than in the muscle tissues of those same fish. Although data were provided on the concentrations of all of the above organic compounds in the other fish

species, the lack of comprehensive geographic coverage for these species limits the interpretation of these data.

Further analyses of the concentrations of other organic compounds in fish were conducted by Malins et al. (1982a). English sole were collected from the Duwamish River, the Hylebos Waterway of Commencement Bay, and in Port Susan. Chinook salmon and Pacific cod were collected from Commencement Bay, Point Jefferson (near Port Madison), and Elliott Bay. The livers of these fish were analyzed for the concentrations of polynuclear aromatic hydrocarbons, hexachlorobenzene, chlorinated butadienes, and chlorinated pesticides. In general, the results agree with those of Malins et al. (1980), i.e., the concentrations of most of the compounds analyzed were higher in the livers of fish caught in either the Hylebos Waterway or the Duwamish River than in those caught in the reference areas (Port Susan or Point Jefferson). The concentrations were generally higher in the demersal English sole than in the semi-pelagic cod and pelagic salmon, reflecting the more intimate association of the former species with regions having sediments contaminated with these organic compounds. Malins et al. (1982a) cautioned, however, that despite clear evidence of chemical contamination of the target species, it is difficult to assess the effect such contamination may be having either on the organisms themselves or on human consumers of these organisms. The very complex association of diverse chemicals makes the identification of cause-and-effect relationships extremely difficult, especially in view of the fact that interactions between these xenobiotic compounds alter the biological effects of the individual compounds. Hence, linking the presence of these chemical contaminants to observed biological changes in Puget Sound will require careful integration of laboratory and field investigations.

McCain et al. (1982) also conducted limited analyses of the concentrations of PAHs in the livers of English sole collected in the Duwamish River, in the Lake Washington Ship Canal, and in McAllister Creek, a reference estuary in Southern Puget Sound. Only low concentrations of PAHs were found in the livers of fish from the two urban estuaries, and they were below the limits of detection in the livers of fish from McAllister Creek. While fish are known to possess the ability to metabolize most aromatic hydrocarbons, one chemical (i.e., napthalene) was frequently detected in the livers of fish from the Duwamish River and the Lake Washington Ship Canal, suggesting that this compound may be more slowly metabolized than other aromatic hydrocarbons.

Gahler et al. (1982) did not detect chlorinated butadienes in Commencement Bay fishes, but elevated levels of hexachlorobenzene, tetrachloroethylene, and trichloroethylene were detected in fishes from the Hylebos Waterway. Pentachloropropene, a strong mutagen, was also tentatively identified in effluent, sediment, and fish tissue samples from the Hylebos Waterway.

Pathology

A variety of pathological conditions possibly caused by chemical contaminants have been reported from various locations throughout Puget Sound and adjacent waters. These include fin erosion, skin tumors, hepatomas and other liver abnormalities, and miscellaneous other conditions. Studies of these pathological conditions have included attempts to describe their exact nature, to estimate their prevalence in different areas of Puget Sound, and to examine associations between the distributions of these pathological conditions and the distributions of known chemical contaminants, especially in areas known to receive waste discharges. Additional studies just completed have attempted to experimentally induce certain pathological conditions through the exposure of fishes to suspected causative agents.

Fin Erosion. According to Wellings et al. (1976a), fin erosion disease (or fin rot, as it is sometimes called) is "a progressive destruction of fin tissue observed in a number of species of freshwater and marine fish",*and this disease may be "acute with ulceration and necrosis or more chronic with epidermal hyperplasia and dermal fibrosis." The etiology is presently unknown, although certain bacterial and chemical agents are strongly implicated.

Wellings et al. (1976a) collected demersal fishes at eight stations in the lower Duwamish River and estuary and examined them for evidence of fin erosion disease. Among 6,547 fishes of 29 species examined, fin erosion was observed only in English sole (*Parophrys vetulus*) and starry flounder (*Platichthys stellatus*). The prevalence of fin erosion among the starry flounder varied seasonally, from a low of 1.6 percent in July to a high of 14.6 percent in March, with an average prevalence of 8 percent. The prevalence of fin erosion among English sole was lower, averaging only 0.5 percent. Although differences in prevalence were noted among stations, they were probably not significant due to small sample sizes. Wellings et al. (1976a) could not identify a causative agent, although they recognized that the Duwamish River sediments contained high concentrations of various chemical contaminants, such as PCBs. They suggested that the available data best fit a multifactorial hypothesis of etiology, stating:

> "It is logical to assume that multiple environmental variables (such as chemical pollutants, physical factors, mechanical injury, etc.) act in some combination on a susceptible genetic background to produce a particular incidence of disease in the population at risk."

Fin erosion is apparently relatively rare in unpolluted, nonindustrialized areas of Puget Sound and adjacent waters. Miller et al. (1974), for instance, in a baseline predischarge survey of the sites of two sewage outfalls (at Stadium,

Washington, on Case Inlet, and at Union, Washington, on lower Hood Canal), reported that among 5,009 fish from 41 species captured at Stadium, none had any degree of fin erosion, while among 14,377 fish from 59 species obtained at Union, only one, a starry flounder, had symptoms of fin erosion.

Sherwood and McCain (1976) attempted to examine possible relationships between fin erosion disease and abnormal body burdens of PCBs, p,p'-DDE, and ten trace metals cations. They collected three starry flounder with fin erosion and three without fin erosion from the Duwamish River estuary, and three starry flounder without fin erosion from a control area, the Nisqually River estuary. Composite tissue samples were taken from each group and analyzed for the above chemicals. Due to the compositing of the samples from each area, no statistical analysis of the resulting data is possible, but there were suggestions that the concentrations of PCBs were higher in the tissues of fish from the Duwamish River than in those from the Nisqually River, especially in the liver samples. The liver PCB concentrations were also higher in fish with fin erosion (18.8 ppm wet weight) than in fish without fin erosion(11.9 ppm wet weight) from the Duwamish River. Similar results were obtained with Dover sole from polluted and unpolluted areas of southern California. There were no notable differences in the concentrations of the other substances analyzed among the three groups from Puget Sound. While Sherwood and McCain (1976) stress that the results do not imply cause-and-effect, they concluded that the similar levels of PCBs in the diseased fishes from the two regions suggest that PCBs may be involved in the disease in both places. More detailed analyses, including other chemical contaminants, are necessary.

Sindermann (1979) conducted an extensive review of pollution-associated diseases of fish, including fin erosion. A number of pollutants have induced fin erosion under laboratory conditions: PCB 1254 (concentrations of 3-5 ppb); crude oil (4-5 ppm in 12 ppt salinity); lead; zinc; and cadmium. Although the mechanism has not been determined by these studies, Mearns and Sherwood (1974) and Sherwood and Mearns (1977) suggest that certain toxic substances remove or modify the protective mucus coat and expose the underlying epithelial tissue to either the toxic effect of chemicals or to bacterial infection. Some experimental evidence supports the latter hypothesis (Sindermann 1979).

Skin Tumors. Skin tumors, classified as angioepithelial nodules, epidermal papillomas, or angioepithelial polyps, are relatively common pathological conditions among certain fishes, especially flatfishes, of Puget Sound. Tumor incidences of 5-10 percent are frequently reported in the English sole (*Parophrys vetulus*), flathead sole (*Hippoglossoides elassodon*), sand sole (*Psettichthys melanostictus*), and starry flounder (*Platichthys stellatus*) at certain collecting sites (Wellings et al. 1976b). Other species occasionally having similar tumors

include Dover sole (Microstomus pacificus), rex sole (Glyptocephalus zachirus), and butter sole (Iopsetta isolepis) (Wellings et al. 1976b; McArn et al. 1968).

In some cases, tumor incidence has been reported to be high in fish from areas near known sources of pollutants. Wellings et al. (1976b) report, for instance, that among some collections of starry flounders from the Nooksack Estuary of Bellingham Bay, over 50 percent of the age group 0 fish have tumors (either angioepithelial nodules or transitions to epidermal papillomas). In other areas far removed from known pollutant sources, tumor incidence is low. Miller et al. (1974) reported that the incidences of skin tumors in English sole from Stadium and Union, Washington, were only 2 percent (7 of 325) and 1.5 percent (28 of 1,849), respectively. Skin tumors are by no means limited to areas near known sources of pollutants, since they have been found in flatfish from virtually all areas of Puget Sound and the adjacent waters (Wellings et al. 1976b).

The geographical variability of tumor incidence is as yet unexplained, but it is characteristic of this disease in all species so far studied. Wellings et al. (1976b) suggest that a possible hypothesis is that as yet undefined environmental variables may play a role in tumorigenesis, although an alternative hypothesis is that genetic susceptibility to unknown tumorigenic agents varies among different fish stocks.

The three types of skin tumors represent different stages of what is apparently the same disease. Angioepithelial nodules are the first to appear, generally in young-of-the-year fish soon after metamorphosis (Angell et al. 1975). These tumors later develop into either epithelial papillomas or angioepithelial polyps (Angell et al. 1975). While the individual tumors increase in size and weight with increasing age of the fish, the incidence of tumorous fish declines with age (Angell et al. 1975), suggesting that tumor-bearing fish disappear from the populations more rapidly than do normal fish (i.e., that they experience higher than normal mortality) (Wellings et al. 1976b).

The fact that angioepithelial nodules are first apparent on recently-metamorphosed juveniles suggests that the "tumorigenic event" may occur at or about metamorphosis (Angell et al. 1975). In flatfishes, metamorphosis includes migration of the eyes to the same side of the head and corresponds with beginning of life on the bottom. If the etiological agent is external to the fish, one would expect angioepithelial nodules to occur with equal frequency on both sides if the "tumorigenic event" occurred during the bilaterally-symmetrical planktonic stage of the fish, but with unequal frequency if it occurred after metamorphosis and is associated with physical contact with contaminated sediments (Angell et al. 1975). While there are significantly more tumors on the eyed side than on the blind side of flathead sole, this relationship does not apply to

tumors of English sole and starry flounder (Wellings et al. 1976b), so the timing and nature of the "tumorigenic event" is unclear.

Campana (1983) reported that the incidence of skin tumors in starry flounder from Bellingham Bay is highest in young-of-the-year and declines to near-zero by age II. A sharp decline in tumor incidence occurred at the same time that the growth rate of tumorous fish deviated significantly from that of nontumorous cohorts. Furthermore, this same period was noted by increasing susceptibility of tumorous fish to stress. These differences between tumorous and nontumorous fish were not apparent prior to age I, but more importantly, these differences strongly suggest differential mortality associated with skin tumors.

Sindermann (1979) has reviewed a number of studies on the induction of tumors by environmental pollutants. Although circumstantial evidence has accumulated from a number of studies, the etiology of skin tumors remains unknown, and its interpretation is complicated by the possibility of multiple factors acting independently or synergistically. According to Angell et al. (1975), possible factors include:

1. Chemical carcinogens and cocarcinogens in the environment, either natural or introduced by man.
2. Induction by virus or parasite.
3. Nutritional deficiencies.
4. Genetic influences or control of susceptibility to carcinogenic agents.

Hepatomas and Other Liver Abnormalities. Hepatomas (liver tumors) and other liver abnormalities represent another type of pathological condition reported in fishes from Puget Sound and adjacent waters. Because detection of these conditions is dependent on dissection and microscopic analysis of the internal organs of the fishes, there have been fewer studies of these conditions than of skin tumors and fin erosion, which can be detected externally. Pierce et al. (1978), Pierce et al. (1980), and McCain et al. (1982) describe the wide variety of liver abnormalities found in Puget Sound flatfishes. Examination of fishes for these conditions has been concentrated on fish collected from heavily industrialized areas of Puget Sound, such as the Duwamish River and Commencement Bay.

McCain et al. (1977) reported finding hepatomas in English sole and starry flounder from the Duwamish River estuary, but too few fish were examined to establish a geographic distribution of tumorous fish within the river. Pierce et al. (1978) reported in greater detail on the occurrence of hepatomas and other liver abnormalities in English sole collected in the heavily-industrialized Duwamish River, at Alki Point and West Point (two areas adjacent to sewage outfalls), and at Point Pully (a control area south of Seattle). The prevalences of

microscopic liver lesions were as follows: Point Pully, 22 percent (4 of 18); West Point, 60 percent (15 of 25); Alki Point, 90 percent (9 of 10); and the Duwamish River, 92 percent (57 of 62). Hepatomas were observed in 32 percent (20 of 62) of the English sole collected in the Duwamish River, but in none of the fish from the other areas. Pierce et al. (1980) reported in greater detail on the occurrence of hepatomas and other liver abnormalities in starry flounder collected in the Duwamish River, at Point Pully, and in the lower reaches of McAllister Creek, an estuary in lower Puget Sound near Olympia. Unusual liver characteristics were noted in 92 percent (127 of 138) of the fish from the Duwamish River, while only 13 percent (5 of 39) of the fish from McAllister Creek had liver abnormalities.

Pierce et al. (1980) concluded that while the etiology of these liver abnormalities is presently unknown, circumstantial evidence suggests that toxic chemicals acting separately or synergistically may be the cause. In support of this suggestion they noted the following:

- Abnormal livers examined microscopically do not show the inflammatory response associated with an active bacterial infection.
- Attempts to isolate bacteria from abnormal livers have been unsuccessful.
- The histopathological characteristics of the liver lesions do not resemble those caused by known viral pathogens.
- The microscopic structure of the liver lesions resembles chemically-induced lesions reported in other fish species.

Dietary deficiencies are also a possible cause, although stomach content analyses did not indicate an insufficient supply of food organisms. Pierce et al. (1978, 1980) noted that the Duwamish River estuary is known to be highly polluted, with high sediment concentrations of PCBs, DDT, DDD (or DDE), copper, and lead, as well as numerous other chemical contaminants.

Malins et al. (1980, 1982a) found a variety of pathological conditions in fish species from various sampling sites throughout Puget Sound. Their analyses concentrated primarily on idiopathic liver lesions in English sole (*Parophyrys vetulus*) and rock sole (*Lepidopsetta bilineata*), since these were the most abundant and widely-distributed fish species examined in this study. Certain pathological conditions, such as liver neoplasms, were restricted to fish from the most chemically-contaminated urban areas. Other conditions, such as preneoplastic lesions and specific degenerative/necrotic lesions were suggestive of such a relationship, although individual fish with these conditions occurred in uncontaminated reference areas as well. Malins et al. (1982a) offered three possible explanations for the occurrence of these conditions in uncontaminated areas: 1) a fish may be exposed to the causative agent(s) in an urban

area and subsequently migrate to a reference area; 2) the lesions may be caused by concentrations of chemicals as low as those found in reference areas; or 3) a variety of other factors (e.g., infectious organisms, physicochemical and physiological factors) may cause these lesions, and while these factors are present in both urban and nonurban areas, more of these factors may be present in urban areas.

The pesticide lindane has been shown to induce liver degeneration in rainbow trout (Couch 1975). Long-term exposure (9-12 months) to 1.6 ppm ammonia induced histopathological lesions in the liver and intestine of trout (Smith and Piper 1975). It is not known whether similar associations can be expected in studies of steelhead.

Other Pathological Abnormalities. Various other pathological abnormalities (e.g., lesions of the gill, kidney, spleen, and gall bladder, as well as certain cardiac abnormalities) have been reported from fish species in Puget Sound and adjacent waters (Malins et al. 1980, 1982a; McCain et al. 1982). While there are reasons to believe that certain of these conditions may be related to chemical contaminants in the environment, either the prevalences of these conditions are very low or the geographical distributions of fish with these conditions are such that clear-cut associations with urban areas or known sources of chemical contaminants are tenuous (McCain et al. 1982).

Studies conducted elsewhere provide little additional information on the causes of pathological abnormalities. Marthur (1962) induced histopathological changes in various organs of salmon by exposure to DDT. Hansen et al. (1971) showed that PCB 1254 induced histopathological features in spot and pinfish. Sindermann (1979) has noted that a number of studies have associated certain heavy metals (cadmium, lead, zinc), chlorinated hydrocarbons (e.g., toxaphene, kepone, trifluralin), and even organophosphorus pesticides (malathion, parathion) with induced skeletal deformities. Von Westernhagen et al. (1981) showed that hatching success in flounder eggs was inversely correlated with ovarian PCB levels. Chlorinated hydrocarbons and certain heavy metals are known to interfere with calcium metabolism. There is some evidence that exposure to pollutants may affect immune responses of fish. One of the best sources of evidence was a multidisciplinary study of short-term sublethal exposure of cunner to cadmium (NMFS 1974).

A wide array of pollutants have been associated with various diseases, lesions, or other abnormalities. Although the weight of the evidence indicates that the associations do exist, it is almost impossible to state positively that the condition is caused by specific environmental contaminants. Most of the studies are flawed by one or more of the following features:

- Dosage levels are elevated over observed environmental levels.
- Synergisms and antagonisms are ignored (with exception of some work on zinc and various environmental variables, [Sindermann 1979]).
- Tests are static acute rather than chronic flow-through.
- Experimental animals are often under stress from confinement.
- Control of contamination is focused on a specific chemical, and the presence of other contaminants is not ascertained.

Pathological Conditions Among Fish in the Vicinity of Municipal Sewage Discharges. Due to the presence of chemical contaminants in municipal sewage discharges, there is reason to suspect that certain pathological conditions of fish may occur in higher prevalence in fish inhabiting areas near sewage outfalls than in unpolluted control areas. If this is the case, such conditions would more likely be observed in demersal fish species than in pelagic fish species, since the former tend to reside in specific areas for longer periods of time, while the latter are only transient residents in a given area. Consequently, there have been several studies of the prevalence of fish diseases in the vicinity of municipal sewage discharges on Puget Sound.

Moulton et al. (1974) examined the prevalences of skin tumors and fin erosion in flatfishes caught in trawls and beach seines at West Point (site of Metro's largest sewage effluent discharge) and Alki Point (site of a much smaller sewage discharge). Only occasional specimens were observed with fin erosion, and Moulton et al. (1974) concluded that it did not appear to be a significant problem in either area. Tumorous English sole (*Parophrys vetulus*) and rex sole (*Glyptocephalus zachirus*) were caught only at West Point, while a single tumorous Dover sole (*Microstomus pacificus*) was caught in the vicinity of each point. The prevalence of skin tumors in trawl-caught young-of-the-year English sole at West Point was quite variable, ranging between 0 and 67 percent, but Moulton et al. (1974) caution that sample sizes were small and that the highly variable percent prevalences were therefore misleading. Moulton et al. (1974) did not sample fish at a control area for comparison with fish caught near the two sewage outfalls.

Miller et al. (1975, 1977) examined the prevalences of fin erosion and skin tumors in demersal fishes collected in trawls and beach seines at West Point, Alki Point, and Point Pully, a control area south of Seattle. There was apparently little reason to believe that the discharge of sewage effluent had been responsible for either condition since fin erosion was not observed at either West Point or Alki Point, and the prevalence of skin tumors was actually higher at Point Pully (control) than at either of the outfall sites.

The only other observations of fish disease made in the vicinity of municipal sewage discharges in Puget Sound and adjacent waters are those near the Anacortes Main and Anacortes Skyline outfalls. Demersal fishes collected near each outfall had prevalences of fin erosion similar to those of demersal fish from a control area, and lower prevalences of superficial tumors, infections, and other abnormalities than the control group. Pelagic fishes collected near these outfalls had no clear cases of fin erosion. Hence, there is little reason to believe that these relatively small sewage discharges have caused an increased prevalence of fish diseases.

Cause-and-Effect Studies of Fish Pathology. There have been few studies of pathological conditions among Puget Sound fishes which have included attempts to identify causes of the observed effects. Of particular interest, of course, is the question of whether the observed pathological conditions are related in any way to pollution of the Sound with chemical contaminants.

Malins et al. (1982a) discussed three approaches to attempting to identify cause-and-effect relationships for the pathological conditions found in fish in their study: 1) comparison of the histopathological and physiological characteristics of the affected fish with characteristics described in the literature for laboratory animals exposed to specific toxic chemicals or infectious agents; 2) statistical methods to correlate the prevalence of fish having certain types of lesions with environmental concentrations of particular classes of chemicals; and 3) laboratory experiments exposing normal fish to suspected causative agents (either individually or in combination) under controlled conditions, and comparison of the resulting effects with lesions found in the field.

Malins et al. (1982a) document a number of similarities between the histopathological conditions observed in fish from chemically-contaminated areas in Puget Sound and those documented in the literature for other animals exposed to a variety of chemical pollutants (e.g., PCBs, DDT, dieldrin, metals, etc.). These similarities suggest that chemical pollutants may be a contributing factor in the prevalence of these conditions in urban areas of Puget Sound.

Using two different statistical techniques, Malins et al. (1982a) were able to show that certain of the histopathological conditions observed in these fish were more prevalent at stations where concentrations of aromatic hydrocarbons and toxic metals in the sediments were high. Malins et al. (1982a) caution, however, that the actual causative agent may be yet another substance which was not measured but whose presence and abundance was correlated with those of the aromatic hydrocarbons and toxic metals. In addition, the fact that two chemically different classes of sediment contaminants are correlated with

the prevalence of fish with similar lesions suggests that these classes of chemicals may interact to cause the lesions. Although it would have been of interest to compare the chemical concentrations of xenobiotic substances in the tissues of the fish with the prevalence of lesions, this was not possible for two reasons: 1) detailed chemical analyses had been performed on too few fish, and 2) aromatic hydrocarbons are rapidly metabolized in fish and are not detectable by routine chemical analysis of fish tissues.

The third approach to ascertaining the causes of the lesions observed in these fish (i.e., exposing normal sole under laboratory conditions to toxic chemicals suspected of being causative agents) was not attempted for two reasons: 1) the long-term culture of sole under simulated natural conditions is difficult; and 2) since the culture of English and rock sole from egg to adult is presently not feasible, experimental animals must be collected from wild stocks which have a high degree of genetic heterogeneity or may have had previous contact with toxic chemicals. Malins et al. (1982a) also caution that different species of fish are known to respond differently when exposed to the same xenobiotic substance, so experiments on one species may not necessarily identify the causative agent of a similar condition in another fish species.

Malins et al. (1982b) conducted a number of experiments relating hydrocarbon exposure to pathology. Three species of juvenile and adult flatfish exposed to oil-contaminated sediment differed substantially in their degree of hydrocarbon accumulation. Pathological changes occurred in the livers of all species tested, but similar changes were also frequently observed in the controls.

High doses of hydrocarbons administered for 2-12 months by Malins et al. (1982b) were shown to produce ultrastructural changes in liver and lens tissues of adult trout. Salmon and flatfish exposed to waterborne hydrocarbons exhibited gill lesions characterized by loss of surface cells. Exposure of embryonic smelt and flatfish to low ppb concentrations of seawater-accommodated crude oil resulted in high mortality at hatching. The eye and brain of the smelt embryos were the primary organs affected, and they showed extensive necrocytosis in later embryonic stages. Disruption of epithelial cell mitochondria and olfactory epithelium were noted in flatfish.

McCain et al. (1982) have recently completed a detailed and comprehensive investigation of the pathology of English sole (*Parophyrys vetulus*) and starry flounder (*Platichthys stellatus*) from Puget Sound. Specimens were collected from the Duwamish Waterway, the Lake Washington Ship Canal, the Snohomish River estuary in Everett, and McAllister Creek, a reference estuary near Olympia. In addition to a detailed macroscopic and microscopic examination of the fishes for a variety of pathological conditions, chemical analyses were conducted to determine the

concentrations of toxic metals, PCBs, and PAHs in the fishes. Finally, laboratory studies were conducted in an attempt to elucidate possible cause-and-effect relationships between sediment-associated chemical pollutants and the abnormalities observed in English sole.

McCain et al. (1982) documented a variety of pathological conditions in the English sole and starry flounder from these four areas. These included: lesions of the skin and fins; liver lesions; gill lesions; and various abnormalities of the heart, gastrointestinal tract, and kidneys. Liver lesions were the most common pathological condition. Preneoplastic and neoplastic liver lesions were found only in English sole and starry flounder from the Duwamish Waterway and the Lake Washington Ship Canal. The prevalences of English sole having either or both of these conditions in these two areas were 20.5 percent (113 of 551 fish) and 20.4 percent (10 of 49 fish), respectively. The prevalences of English sole with liver neoplasms in these two areas were 12.9 percent (71 of 551 fish) and 8.4 percent (4 of 49 fish), respectively. The prevalence of starry flounder with liver neoplasms was only 1.1 percent (3 of 279 fish) in the Duwamish Waterway. Among fishes collected in the Snohomish River and in McAllister Creek, the only non-neoplastic liver lesions were found, and the prevalences of these conditions were very low in each area. Among the pathological abnormalities of the other organ systems, either the prevalences of these conditions were very low or the geographical distributions of fish with these conditions were such that there were no clear-cut associations with urban areas or known sources of chemical contaminants.

McCain et al. (1982) reported that the concentrations of PCBs in the livers of English sole and starry flounder reflected the relative concentrations of these compounds in the sediments where the fish were collected. Hence, the highest concentrations of PCBs (17-161 ppm dry weight) were found in the livers of English sole collected in the Duwamish Waterway, whose sediments are known to be contaminated with PCBs, while the lowest concentration of PCBs (0.5 ppm dry weight) was found in a composite sample of livers from English sole collected in McAllister Creek, the control estuary. There were no clear trends in the tissue concentrations of cadmium, chromium, copper, lead, or zinc. Tissue concentrations of most of the aromatic hydrocarbons were low, which reflects the ability of flatfishes to rapidly metabolize these compounds to undetectable metabolites, although one such compound, naphthalene, was frequently found in the livers of English sole from the Duwamish Waterway but not in those from McAllister Creek.

Three types of laboratory experiments were conducted by McCain et al. (1982) in an attempt to evaluate whether English sole may be adversely affected by exposure to chemically-contaminated sediments. In the first, McCain et al. (1982) were able to show that the mortality rate of English sole maintained

for up to 3 months in aquaria containing Duwamish Waterway sediments was not significantly higher than that of English sole maintained in similar aquaria with control sediments. There were, however, possible problems with chemical contaminants in the control sediments, and the experiment should be repeated with better control sediments. The second set of experiments, which included intraperitoneal injections of juvenile English sole with extracts of either contaminated Duwamish Waterway sediments, reference sediments, or a carrier (corn oil) only, revealed that the first treatment (injection with the extract of contaminated sediment) caused significantly higher mortality than did either of the other treatments. None of the major histopathological conditions found in naturally-occurring fishes was induced in these experimental animals, however. The third set of experiments was designed to evaluate the uptake and fate of benzo[a]pyrene (BaP), a known carcinogen, in English sole. The fish were exposed to a reference sediment contaminated with radioactively-labeled BaP, and then the concentrations of BaP in the blood, liver, muscle, and gall bladder of the fish were measured. The highest concentrations of BaP and its metabolites were detected in bile and in liver tissue.

While McCain et al. (1982) had attempted to elucidate the causes of pathological abnormalities observed in demersal fishes from urban areas of Puget Sound, they concluded that the causes remain unknown. They noted that the similar prevalences of English sole with liver neoplasms in the Duwamish Waterway and the Lake Washington Ship Canal, despite 3-11 fold lower sediment concentrations of PCBs in the sediments at the latter site, suggested that exposure of these fish to PCB-contaminated sediments may not be directly related to liver neoplasms in the fish. It should be noted, however, that the size of the Lake Washington Ship Canal sample was too small (49 fish) for the prevalence (8.4 percent) to be given much credence. The experiments with the intraperitoneal injections of sediment extracts do not "prove" that a chemical pollutant in sediments is not responsible for the pathological conditions observed in natural fish populations since: 1) exposure by injection may not simulate natural exposure, 2) the experimental fish may not have been of a susceptible age, or 3) a longer exposure time may be required. McCain et al. (1982) were able to show, however, that contaminated sediments from a known heavily-industrialized estuary (Duwamish Waterway) may contain chemicals which are potentially toxic to English sole, and that these fish are able to assimilate a known carcinogenic compound (BaP) from the sediments. Further study will be required to elucidate the causes of the diverse pathological conditions of these fish.

Benthic Macroinvertebrates

Ecology

Analyses of benthic community structure and of abundances of individual species have been conducted near several pollutant sources in Puget Sound, including sewage discharges, industrial discharges, and dredged material disposal sites.

Surveys of benthic macroinvertebrates have been conducted near several sewage discharges in Puget Sound. Most of the surveys were conducted in support of applications for modified discharge permits under the 301(h) program administered by EPA. The available studies are summarized in Table 7-1. In theory, these studies should demonstrate minimal effects on benthos because municipal outfall sites in Puget Sound are generally selected for oceanographic characteristics that result in rapid dilution and dispersion of the effluent. Results of these studies should be considered with appropriate caution because sampling may not have occurred in areas of deposition of the discharged particulates.

Metro's West Point discharge was studied more intensively than any other sewage discharge in Puget Sound. In a comprehensive survey of benthic infauna at 100 sites in the Central Basin, including several near the West Point outfall, Thom et al. (1979) concluded that the effect of the discharge was related to limited organic enrichment of areas near the outfall. The observed effects included an apparent increase in filter-feeding species. The author's conclusion was based on evaluation of ITI values, total numbers of individuals, and total biomass.

In a subsequent analysis of the Thom et al. (1979) data, Word and Striplin (1981) attempted to separate nutrient-related and toxic effects of the West Point discharge. Word and Striplin (1981) concluded that:

- Total macrofaunal abundances were below natural background levels near the discharge.
- Abundances of suspension-feeding taxa were reduced near the discharge.
- Abundances of miscellaneous phyla (e.g., echinoderms, bryozoans) were reduced near the discharge.

The authors state that these results, combined with the analysis of ITI values, suggest that macroinvertebrate communities near the West Point discharge were responding to toxic effects of discharged particulates. Word and Striplin (1981) also characterized the toxicity sensitivities of major infaunal taxa as follows (from most sensitive to least sensitive): echinoderms, crustacea, molluscs, and polychaetes.

Table 7-1. Summary of Studies of Benthic Macroinvertebrate Communities Near Sewage Discharges in Puget Sound.

Outfall Name	Location	Number of Sampling Stations	Biological Variables	Reference
West Point	Main Basin	100	ITI, biomass, total abundance	Thom et al. 1979
West Point	Main Basin	100	ITI, biomass, total abundance with abundances of major taxa	Word and Striplin (1981)
Tacoma North End	Commencement Bay	6	Abundance, community variables	City of Tacoma (1979a)
Tacoma Western Slopes	Narrows	6	Abundance, percent cover	City of Tacoma (1979c)
Anacortes Main	Guemes Channel	4	Abundance, community variables	City of Anacortes (1979a)
Anacortes Skyline	Rosario Strait	3	Abundance, community variables	City of Anacortes (1979b)
Port Angeles	Port Angeles Harbor/ Strait of Juan de Fuca	6	Abundance, community variables	Northern Tier Pipeline Company (1979)
Steilacoom	Main Basin	2	Qualitative observations	Town of Steilacoom (1979)
Richmond Beach	Main Basin	6	ITI, species abundances	Word et al. (1981)
Denny Way CSO	Elliott Bay	19	Species abundance	Armstrong et al. (1980)

Research on the applicability of the ITI to detecting pollutant effects is currently being conducted at the University of Washington (Word pers. comm.). Specific areas of investigation include:

- o Selection and grouping of Puget Sound taxa.
- o Numerical review of the index algorithm.
- o Response of index to water depth.
- o Effects of screen size on index values.
- o Isolation of toxic effects.

All other sewage discharges studied in Puget Sound are considerably smaller than West Point. In general, any observed biological effects have been associated with minor modifications in community structure of the infaunal benthos. Several of these smaller discharges are also located in areas of high current veloci- ties where sewage particles do not accumulate in the discharge vicinity (e.g., Tacoma Narrows, Guemes Channel).

Seattle Metro has sponsored a series of studies of the effects of municipal wastewater discharges on intertidal biota (Armstrong et al. 1977; Thom et al. 1977; Staude et al. 1977). The studies were conducted at five beaches in the Central Basin (including West Point) from 1971-1975.

The studies by Armstrong et al. (1977) of epifauna and infauna (1.0 mm and 6.0 mm screen sizes) indicated considerable between-beach variability in biological characteristics. The authors attributed the results to differences in beach stability and substrate composition. Based on analyses of organism density, biomass, diversity, and individual species abundances, no effects of the sewage discharges located at West Point, Alki Point, Carkeek Park, and Richmond Beach could be detected for intertidal fauna.

Studies of intertidal and subtidal algae were conducted by Thom et al. (1977) at the same five beaches that were sampled for macrofauna. Differences in community structure and growth rates were detected among beaches. The total number of species present was generally lower at the four beaches near sewage discharges than at the Lincoln Park control beach. In the subtidal communities, the kelp Nereocystis was more dense and slower growing at West Point when compared with Lincoln Park. Alternatively, Laminaria saccarina grew significantly faster at West Point than at Lincoln Park. The authors noted that water turbidity was considerably higher at West Point than at Lincoln Park at the time of sampling.

Overall, the intertidal studies near West Point indicate that water quality conditions were improving during 1971-1975 (Staude et al. 1977). If the West Point discharge is affecting intertidal communities, the effects are manifested only as minor changes in community structure and function.

Documentation of effects of chlorination of sewage on benthos in Puget Sound is lacking. The California Department of Fish and Game (1981) discovered that Cancer magister treated with relatively high dilutions of chlorine-treated sewage displayed slower turnover (righting) responses than those treated with untreated sewage, including less diluted untreated sewage. Behavioral effects such as these may play a role in minor changes in community structure around the West Point outfall.

Benthic macroinvertebrate assemblages near a combined sewer overflow (CSO) in Elliott Bay were studied by Armstrong et al. (1980). Sampling areas at a depth of 9 m from directly offshore to about 150 m northwest of the CSO had a modified benthic community structure when compared with surrounding areas. The effects of the CSO were manifested as enhanced abundances of subsurface deposit feeders (primarily the polychaete, Capitella capitata) and slightly lower species richness near the CSO. Total volatile solids were enhanced near the CSO and were correlated with the biological effects. Sediment metal concentrations displayed no clear trends in the study area. Overall, the effects of the CSO were found to be highly localized.

Studies of the effects of pulp and paper mill wastes on benthic macroinvertebrates were conducted during the period 1964-1966 near Bellingham, Everett, and Port Angeles (FWPCA and WSPCC 1967). Thick sludge deposits were observed near the mill discharges at all three sites. The heaviest deposits were found in the upper harbor areas with limited circulation. Total volatile solids of the sediment in such areas exceeded 10-15 percent.

At all three sites the areas of sludge accumulation occurred over much of the harbor area. At Bellingham and Everett, the areas of greatest sludge accumulation were found to contain no macrofaunal benthos. Areas of lesser sludge accumulation were characterized by very low species richness and abundance.

Since the pulp mill surveys had study design limitations, some of the data should be interpreted only in a semiquantitative manner. Nevertheless, the studies were adequate to demonstrate the severe effects of previous pulp mill discharge into areas of limited circulation.

The benthic infauna of Everett Harbor and surrounding areas were again sampled in 1973 (Malkoff 1976). Sampling was conducted along 11 transects extending from near the pulp mill diffusers in Everett Harbor to an area about 4.5 km southwest of the diffusers in Port Gardner. The data indicated that a slight improvement in the numbers and kinds of infaunal organisms had occurred since the 1967 sampling. There was also an indication that total volatile solids in the sediments had decreased during that period. Both taxon richness and number of individuals increased with increasing distance from the pulp mill outfalls. Infaunal communities near the discharges were limited mainly to

the opportunistic polychaete Capitella capitata and nemerteans. Near the outfalls, total numbers of individuals were less than 2,000 per m^2, while densities in areas away from the discharges were about 14,000 per m^2.

Infaunal sampling was again conducted in Everett Harbor and Port Gardner in 1974-1975 following a reduction in effluent discharge from the pulp mills (Malkoff 1976). However, no conclusions were reached about the possible recovery of benthic communities. In the 1974-1975 surveys, sampling was not conducted in the immediate discharge vicinity, and different sampling gear was used.

Pearson and Rosenberg (1978) have examined change in benthos as a function of effects of paper mill waste on benthic populations in Scotland. Rosenberg (1973) documented the change in benthic community structure following closure of a paper mill. Pearson (1975) studied in another location the benthic community around a paper mill outfall for 10 years, beginning 3 years before discharge began. The changes in community structure at the two sites were remarkably mirrored. During their analysis (Pearson and Rosenberg 1978) of the data, an effort was made to determine whether early indications of stress could be identified at the population or community level. Close scrutiny indicated that the only significant indication of stress was the increased abundance of "middle order" species, i.e., the neither rare nor common species based on a log normal distribution analysis. These studies are fairly unique in that they address the potential recovery rate of the benthic community and suggest a useful index of stress at the community level.

Malins et al. (1980, 1982a) sampled macroinvertebrate infauna at various sampling sites in Puget Sound including industrial and nonindustrial areas (see previous section on Fish Ecology). Although the studies represent a comprehensive sampling of infauna in many industrialized and nonindustrialized areas of Puget Sound, they are of little value in assessing cause-and-effect relationships. The major limitations of the studies are associated with:

- Combining samples from several depths which differ among sampling sites.
- Taxonomic identification of only Infaunal Trophic Index (ITI) taxa.
- Deletion of oligochaetes from sample identifications.

The reliance on ITI taxa in assessing the community-level response of benthic infauna presents considerable interpretive problems. The ITI list used by Malins et al. (1980, 1982a) contains 48 taxa, consisting of 25 genera, 19 families, and 4 higher taxa. These taxa are unequally divided among four feeding types (e.g., 17 taxa of suspension and surface detritus feeders and 6 taxa of subsurface deposit feeders). Thus, by only counting ITI taxa, an assemblage dominated by suspension feeders may appear to have a higher taxon richness or diversity

than an assemblage dominated by deposit feeders. Because of the unequal allocation of ITI taxa to feeding groups, the community parameters are biased, and the actual community structure may be considerably different than indicated in the study results. Deletion of oligochaetes from the sample analyses also results in a considerable bias toward reduced abundance and taxon richness, especially in lower saline depositional environments (e.g., near the heads of inlets).

In an attempt to relate calculated infaunal community variables to environmental variables, Malins et al. (1980, 1982a) conducted simple and multiple regression analyses. Most toxic constituents were negatively correlated with the three ITI-related variables (richness, abundance, and ITI); however, individual correlation coefficients were relatively low (Malins et al. 1980). Stepwise multiple regression analyses resulted in the highest multiple coefficient of determination of 0.59 for diversity when all variables were entered into the equation (Malins et al. 1982a).

Because of the aforementioned study design limitations in the infauna studies of Malins et al. (1980, 1982a), the predictive value of the statistical relationships is extremely limited. The ITI can be useful in detecting pollutant-induced effects; however, its use in examining effects of toxic pollutants results in severe interpretive limitations.

A comprehensive study of the effects of dredged material disposal on macrofaunal benthos was conducted at the Elliott Bay dredged material disposal site (Bingham 1978). The study is important from a cause-and-effect perspective because it documents spatial response gradients relative to dredged material deposition rates. In addition, the recovery of the benthos was monitored for a period of 9 months after disposal.

Significant decreases in taxa number, diversity, abundance and biomass were detected at the actual disposal mound and at adjacent stations. Greatest effects were observed at the disposal mound where deposition of dredged material exceeded 2 m in depth. During the study period there was incomplete recovery of the benthos at the center of the disposal area and adjacent areas. For example, mean biomass near the disposal area center was only about 33 percent of reference values 9 months after disposal.

Stations at the corner of the disposal area (170 m from the center) were covered by less than 0.5 m of dumped material. These sites displayed only moderate effects relative to the central area stations and had recovered completely within 3 months after disposal.

The only statistically significant difference observed by Malins et al. (1982a) in a sediment recolonization experiment was a lower taxon richness (presumably only ITI taxa) in local sediment exposed in the Duwamish Waterway when compared with

recolonization of reference sediment at that site. Although these results are in correspondence with the findings of lower overall taxon richness in the station group, including the Duwamish Waterway, the exclusive analysis of ITI taxa limits the interpretation of the results.

A study of the effects of water quality on the colonization rates of artificial substrates is currently being conducted by A. Schoener with support by NOAA (Long pers. comm.). Substrates are exposed in situ at several industrialized areas (e.g., Commencement Bay Waterways) and at two reference areas. Preliminary results indicate depressed colonization rates, based on species number, after 12-months' exposure in the industrialized waterways (Long 1982).

The effects of experimental oiling and subsequent recovery of benthic invertebrate communities was studied at four sites near Sequim Bay and Discovery Bay on the Strait of Juan de Fuca (Vanderhorst et al. 1980a). Experiments with Prudhoe Bay crude oil were conducted for a period of 15 months in soft bottom and hard bottom substrates. Overall, recovery time for oiled habitats varied according to substrate type, tide level, and organism feeding type. The following times to full recovery were estimated:

- Sand (1,758 ppm) - 31 months.
- Commercial clam bed (2,500 ppm) - 46 months.
- Experimental hard substrate (500 g/m^2) - 3-13 months (loss of oil).

Two species (Leptochelia dubia [a tanaid crustacean] and Exogone lourei [a syllid polychaete]) were identified as good indicators of recovery from oil pollution effects in the Strait of Juan de Fuca.

Toxicity Bioassays

A variety of bioassays have been performed using Puget Sound benthic organisms. The available studies are summarized in Table 7-2. Most of the studies have used sediment samples as the exposure medium and have ranged from limited surveys of a few contaminated areas to broad-scale surveys of many sites throughout the Sound. Most of the studies have used mortality as the response variable; however, recent and ongoing research is also being conducted on sublethal responses (e.g., respiration, motility, reproduction).

Several laboratory toxicity studies have been conducted to determine effects of contaminated water or sediments on benthic invertebrates in Puget Sound. Swartz et al. (1982) conducted 175 bioassays on Commencement Bay sediment samples using the infaunal amphipod, Rhepoxynius abronius. The studies were conducted by exposing the test organism to a 2 cm layer of sediment. Two major conclusions were reached:

Table 7-2. A Summary of Sediment Bioassay Tests on Puget Sound Organisms.

Test Species	Exposure Method	Exposure Time	Response Variable	Location or Source(s)	References
Rhepoxynius abronius (Amphipoda)	sediment, laboratory	240 h	mortality, moribundity	17 sites, Puget Sound	Ott et al. (1982)
Rhepoxynius arbonius (Amphipoda)	sediment, laboratory	240 h	mortality	175 samples, Commencement Bay	Swartz et al. (1982)
Gasterosteus aculeatus (Three spine stickleback) Eogammarus convervicolus Monopylephorus cuticulatus (Oligochaeta)	water, sediment/ water slurry	-	mortality	97 samples, Puget Sound	Chapman et al. (1982)
Monopylephorus cuticulatus (Oligochaeta)	water, elutriate	-	respiration	97 samples, Puget Sound	Chapman et al. (1982)
Fish cell culture	water/sediment extracts	-	anaphase aberration	97 samples, Puget Sound	Chapman et al. (1982)
Acartia tonsa and Tigriopus californicus (Copepoda)	elutriate, suspended particulate	24 h	mortality	Duwamish River (2 sites)	Shuba et al. (1978)
Rangia cuneata (Mollusca) Palaemonetes pugeo (Decapoda)	sediment	14 day	mortality, bioaccumulation	Duwamish River (2 sites)	Shuba et al. (1978)
Protothaca staminea Macoma inquinata (Mollusca) Glycinde picta (Polychaeta) Rhepoxynius abronius (Amphipoda) Cumaceans (several spp.)	sediment	240 h	mortality	Duwamish Waterway (3 sites), Elliott Bay (1 site), Puget Sound (1 site)	Swartz et al. (1979)

- Sediments from central Commencement Bay, including the two designated disposal sites, were not acutely toxic.
- Areas of both high and low toxicity were detected in the waterways and other nearshore areas of Commencement Bay.

There was a very high level of spatial heterogeneity in the toxicity of waterway sediments. Samples resulting in 100 percent mortality were in some cases collected directly adjacent to sites that resulted in negligible mortalities (i.e., not different from controls). Within the waterways the highest mortalities were generally associated with intertidal sediments, while the lowest mortalities were associated with mid-channel sediments.

The studies of Swartz et al. (1982) provide important evidence for cause-and-effect relationships since the distribution of amphipods at the sediment sampling sites was determined. Amphipod distribution was correlated with the level of sediment toxicity, and phoxocephalid amphipods (i.e., same family as the bioassay test species) were absent from the waterways.

In an earlier series of experiments, Swartz et al. (1979) conducted similar sediment bioassays on five different test groups: *Protothaca staminea* and *Macoma inquinata* (Bivalvia), *Glycinde picta* (Polychaeta), *Rhepoxynius abronius* (Amphipoda), and several cumacean species. Test sediment sources included three sites in the Duwamish Waterway, and adjacent sites in Elliott Bay and Puget Sound. Overall survivals (of all five taxa) were significantly less than Yaquima Bay controls in all but the Duwamish mouth sediments. There were considerable interspecific differences in the sensitivities of test organisms. *Glycinde picta* and *P. staminea* were not significantly affected by any of the test sediments. In contrast, *R. abronius* experienced significantly higher mortalities at three of the five sediment exposures relative to controls.

A comprehensive sediment bioassay program was conducted by Chapman et al. (1982b) under sponsorship of NOAA. Sediment samples were collected from 97 sites in Elliott Bay, Commencement Bay, Sinclair Inlet, Port Madison, and Birch Bay. Three types of bioassays were conducted: acute lethal (stickleback, amphipod, and oligochaete), sublethal respiratory (oligochaete), and anaphase aberration (fish chromosomes). The test procedures differ from those of Swartz et al. (1982) since test organisms are exposed to water and sediment slurries in the acute bioassays.

In contrast to the study by Swartz et al. (1982), the results of acute bioassays conducted by Chapman et al. (1982b) showed essentially no indication of lethal conditions at the sites surveyed. The only acutely lethal response was observed using sediments from a site near the Denny Way CSO. The

difference in results may be due in part to methodological differences and in part to differential sensitivities of test species.

Sublethal bioassays conducted by Chapman et al. (1982b) indicated potentially toxic conditions (respiratory or cytogenic) at numerous sites. Forty of the 97 sediment samples resulted in respiratory stress in oligochaetes, while only one toxic response was observed in control areas.

Sediment extracts from many of the test locations caused chromosomal damage in fish cells. Highest levels of mutagenicity were detected at sites in outer Elliott Bay, Denny Way CSO, inner Commencement Bay, and Blair and City Waterways. There was only a 42 percent correspondence between cell toxicity and anaphase aberration, indicating that two separate effects may have occurred.

Based on combined test results (lethality, respiratory toxicity, and mutagenicity), the areas of greatest toxic effects are were ranked as follows:

- Denny Way CSO.
- City Waterway (Commencement Bay).
- Hylebos and Blair Waterways (Commencement Bay).

The authors also noted patchiness of toxic effects (in same manner as Swartz et al. 1982) in sediments from Commencement Bay and the waterways.

The primary limitation of the Chapman et al. (1982b) is the lack of analyses of sediment contaminants. Thus, the bioassays serve to identify areas with toxic sediments but do not provide information on the causative agent(s). The sediment bioassay program is currently entering into Phase II in which sediments from 23 selected sites will be analyzed for contaminants and used in the following bioassay series (Long pers. comm.):

- *Capitella capitata* (life cycle).
- Surf smelt egg and larvae.
- Oyster larvae.
- Fish cell toxicity.

A series of amphipod bioassays using sediment samples from 17 Puget Sound sites was conducted by Ott et al. (1982). Test organisms were the infaunal amphipod species (*R. abronius* [Phoxocephalidae] and *Eohaustorius washingtonianus* [Haustoriidae]). Organisms were exposed directly for 240 hours to the sediments in a closed recirculating seawater system.

Sediments from four sites (one from Seattle Waterfront, two from Duwamish Waterway, and one from Sinclair Inlet) caused significantly lower survivals of *R. abronius* than the control

station sediments. Similar to the observations of Swartz et al. (1982), there was a spatial heterogeneity in the toxic response within localized areas. For example, sediments from two sites in the Duwamish Waterway did not result in significantly different mortalities from control sediment, while sediment from two other Duwamish sites caused significant mortalities. Interspecific comparisons revealed that R. abronius is more sensitive to toxic sediments than E. washingtonianus.

A series of in situ bioassay experiments was conducted by Malins et al. (1982a) to determine the effects of organism exposures at urban and nonurban (reference) areas. Juvenile crabs (Cancer gracilis) and bivalve molluscs (Macoma spp., Tapes phillippinarum and Protothaca staminea) were exposed in cages at the Duwamish, Hylebos, and City Waterways, at the Seattle Waterfront, and at a reference area in Port Susan. Colonization of defaunated (frozen) sediment cores was also examined at each of the sites.

Crab survival after 8 weeks was lowest in the Duwamish Waterway (25 percent), intermediate at the reference and City Waterway sites, and highest at the Seattle Waterfront and Hylebos Waterway sites (both 100 percent). In general, tubular metaplasia of the hepatopancreas was the only observed significant difference in the frequencies of histopathological abnormalities in surviving crabs from the Hylebos Waterway, City Waterway, and Seattle Waterfront. A high survival rate was observed in Macoma spp. exposed at all of the urban sites.

Malins et al. (1982b) tested effects of low (15-150 ppb) waterborne hydrocarbons on a number of benthic invertebrates. At these concentrations nudibranchs failed to locate mating conspecifics and suffered impaired reproduction and embryological abnormalities. Shrimp overt feeding behavior and sea urchin pedicellarial defensive responses were reduced by half. Exposure to naphthylene (1-100 ppb) impaired fertilization and embryonic development of mollusc larvae and survival of crustacean larvae.

The primary result of the available bioassay information is the identification of sites within Puget Sound that have sufficient sediment contamination to cause a measurable response in test organisms. The studies have been concentrated in industrialized areas of Puget Sound such as Commencement Bay, Elliott Bay, and Sinclair Inlet. Highest sediment toxicities have been observed in these areas, especially in associated waterways. The available information also indicates that sediments from areas away from industrial or municipal pollutant sources are generally nontoxic to the species tested.

Bioaccumulation

Schell et al. (1977) measured trace metals in six species of bivalve molluscs from seven central Puget Sound locations

(West Point, Lincoln Park, Alki Point, Carkeek Park, Richmond Beach, and Point No Point and Blake Island as background). The organisms were collected from intertidal sites. Schell et al. (1977) concluded that concentrations of several metals (e.g., lead, chromium, and zinc) were higher in mussels at the sites near sewage outfalls than at background stations. However, it should be noted that the sites near sewage outfalls (e.g., West Point, Alki Point, and Carkeek Park) are also near metropolitan Seattle where intertidal organisms are potentially exposed to a variety of municipal and industrial sources of metals. Schell et al. (1977) observed no detectable gradients in tissue concentrations of lead and mercury in intertidal algae, mussels, and clams at the six stations from Lincoln Park to Richmond Beach.

A laboratory study of potential bioaccumulation of metals in littleneck clams (Protothaca staminea) exposed to diluted West Point sewage effluent was conducted by Stober et al. (1977). Organisms were exposed for a period of 8 weeks under continuous flow conditions. Although tissue concentrations of copper and zinc were higher in organisms exposed to 10 percent effluent by volume, the increases were not statistically significant. Mean whole-body copper concentrations were approximately two times higher in clams exposed to diluted effluent than in control clams.

Past discharges from a chloralkali plant located on Bellingham Bay have resulted in considerable contamination of sediments and invertebrate organisms (Bothner and Piper 1973; Rasmussen and Williams 1975). Intertidal biota (e.g., Mytilus edulis and Hemigrapsus spp.) had mean mercury concentrations for a variety of tissues ranging from 0.04 to 0.30 mg/wet kg. Tissue concentrations of mercury in intertidal organisms from Bellingham Bay were about an order of magnitude higher than those from nearby Birch Bay. Mercury in muscle tissue of Dungeness crabs was about 4.5 times higher in Bellingham Bay (0.23 mg/wet kg) than in Samish Bay (Rassmussen and Williams 1975). Roesijadi et al. (1981) sampled mussels in Bellingham Bay following a period of reduced mercury discharges from the chloralkali plant. In 1978, tissue concentrations in mussels from near the plant discharge were about 14 percent and 28 percent of the values reported for 1970 and 1973, respectively. However, mercury concentrations in Bellingham Bay mussels remain about three times higher than those for mussels occurring in uncontaminated areas of Puget Sound.

Gahler et al. (1982) compared muscle tissue concentrations of metals in Dungeness crabs from Commencement Bay (Hylebos and City Waterways) and Discovery Bay. Copper and lead concentrations were higher in the Commencement Bay waterway samples; however, other metals were measured at similar concentrations (e.g., mercury, zinc, and cadmium) or were higher at the Discovery Bay reference site (e.g., arsenic and nickel).

As part of a Class II survey of the ASARCO copper refinery (WDOE 1979), intertidal mussels (M. edulis) were sampled near

the discharges and analyzed for concentrations of lead, copper, zinc, cadmium, chromium, nickel, and arsenic. Although the survey indicated that mussels near the refinery discharges may be accumulating considerable levels of some metals (e.g., copper and zinc), the results are somewhat anomalous. Arsenic concentrations ranged from 1.4-7.2 mg/wet kg (depending upon sampling station and analytical laboratory) in mussels from near the refinery. In a survey of 22 stations in Southern Puget Sound, Price (1977) reports a medium arsenic concentration of 7.2 mg/wet kg. Olson and Shell (1977) report a mean control value of about 0.6 mg/wet kg for mussels in Puget Sound. Thus, although there is a relatively high discharge of arsenic at the refinery, the actual bioaccumulation potential is not clear from available data.

Arsenic concentrations in invertebrate organisms from near the ASARCO smelter and from distant Puget Sound sites were analyzed by Crecelius (1974). Test organisms included several species each of starfish, crabs, and shrimp. Abnormally high concentrations of arsenic (reading 227 mg/dry kg in hermit crabs) were detected in crustaceans living on the smelter slag pile. However, these data must be interpreted with caution since whole organisms were analyzed and the arsenic may have been ingested or adsorbed rather than bioaccumulated. Analyses of mussel (*M. edulis*) tissue revealed that arsenic concentrations near the smelter were similar to those at distant sites (6-14 mg/dry kg).

Two studies have been conducted on the bioaccumulation of metals and PCBs following dredge material disposal in Elliott Bay. Teeny and Hall (1977) examined the uptake of mercury and chromium, and Stout and Lewis (1977) evaluated bioaccumulation of PCBs from the contaminated sediment. Pink shrimp (*Pandalus borealis*) were sampled at the disposal site and at a reference site. Mussels (*Mytilus edulis*), sea cucumbers (*Parastichopus californicus*), and spot shrimp (*Pandalus platyceros*) were exposed in mesh cages at the disposal site. Exposure of caged organisms for up to 3 weeks and collection of indigenous organisms at periods up to 39 weeks after disposal revealed no uptake of mercury, chromium, or PCBs. It should be noted, however, that organisms used in the cage experiments already contained substantial levels of PCBs because of existing contamination in the Duwamish Waterway and Elliott Bay.

Clams (*Rangia cuneata*) and grass shrimp (*Palaemonetes pugeo*) were found to bioaccumulate PCBs when exposed to Duwamish River sediment slurries of from 0.5-5 percent for a period of 14 days (Shuba et al. 1978). After the exposure to 5 percent sediment slurries, tissue PCB concentrations of both species were approximately equal to the sediment concentrations (0.38-0.66 ppm). Lead and zinc were the only metals bioaccumulated during the test period.

Mowrer et al. (1977) analyzed PCB concentrations in mussel tissue and sediments at 18 sites in Southern Puget Sound.

Highest tissue concentrations were measured in samples from the industrialized areas near Seattle, Tacoma, and Bremerton. In general, highest mussel tissue concentrations of PCBs were observed in areas of high sediment concentrations. The sediment-tissue relationship is not absolute, however, and some sites (e.g., Magnolia) with relatively low sediment PCB concentrations had high mussel tissue concentrations. Alternatively, a station in Sinclair Inlet had elevated sediment concentrations on PCBs but a relatively low concentration in mussels.

Comparison of crabs (juvenile Cancer gracilis) and clams (Macoma spp., Tapes phillippinarum, Protothaca staminea) exposed in the Hylebos Waterway with reference organisms indicates that several groups of organic compounds were bioaccumulated (Malins et al. 1982a). After a 10-week exposure in the Hylebos Waterway, the clams accumulated relatively high levels of PCBs (1.8 mg/dry kg) compared to reference samples (0.06 mg/dry kg). The concentration of total aromatic hydrocarbons in the Hylebos-exposed clams was 15 mg/dry kg compared to a reference concentration of 0.97 mg/dry kg.

PCB levels in Dungeness crabs were considerably elevated in the industrialized waterways of Commencement Bay (0.06 mg/wet kg) when compared with Discovery Bay samples (<0.01 mg/wet kg) (Gahler et al. 1982). Tissue PCB concentrations in waterway crabs were well below the FDA Action Level of 5 mg/wet kg. DDE was detected at low concentrations (0.002-0.005 mg/wet kg) in Commencement Bay and Discovery Bay crabs.

Pathology

Malins et al. (1982a) studied pathological conditions in shrimp (Crangon alaskensis and Pandalus spp.) and crabs (Cancer spp.) collected from the sampling sites identified in the section on Fish Ecology. A variety of histopathological lesions and parasitic infections were identified; however, the abnormalities were considered to be idiopathic. Necrotic and nodular lesions had relatively high prevalences (in some cases 30-80 percent) in shrimp and crabs collected from urban areas (e.g., Commencement Bay Waterways, Duwamish Waterway, and Elliott Bay). The prevalences of these lesions were generally lower in organisms collected from nonindustrialized areas. Although the results suggest that adverse water quality conditions may be causing diseases in invertebrate species (including species of recreational or commercial importance), the study should not be considered definitive. The major limitation is in the low numbers of organisms examined, which precludes meaningful statistical analyses of the data.

Plankton

Ecology

There have been relatively few investigations of the effects of pollution on the ecology of Puget Sound plankton. Due to their transient nature and their extremely pronounced seasonal variations in both abundance and species composition, it is much more difficult to define resident populations, and therefore much more difficult to follow changes in those populations which might be correlated with the effects of known pollutants. The most extensive studies to date have examined possible effects of the discharge of municipal sewage on the ecology of phytoplankton and zooplankton communities. These studies have included measurements of phytoplankton productivity in the vicinity of the largest sewage discharge on Puget Sound (West Point), analyses of the distribution of ichthyoplankton in the vicinity of West Point, and very limited studies of phytoplankton and zooplankton community composition in the vicinity of three of Tacoma's municipal sewage discharges. Limited studies have been conducted of the possible effects of pulp and paper mill discharges on both phytoplankton and zooplankton community composition, as well as on phytoplankton productivity. In Liberty Bay, a study was made of possible effects of the discharge of metal plating wastes and other wastes from the Keyport Navy Torpedo Station on phytoplankton populations within the bay. Another limited study has been conducted on the effects of the disposal of dredge spoils in the south Sound on phytoplankton productivity.

Metro has sponsored several studies (Anderson 1976; Campbell et al. 1977; Ebbesmeyer and Helseth 1977) whose aim was to assess possible effects of the West Point sewage effluent discharge on the level of phytoplankton standing stock and primary productivity in the Central Basin. None of these studies dealt with possible changes in phytoplankton community composition.

The University of Washington researchers (Anderson 1976; Campbell et al. 1977) concentrated on the analysis of phytoplankton standing stock (as chlorophyll a concentration) and primary productivity (measured by simulated in situ incubation) at a station approximately 2.4 km (1.5 miles) north of the West Point outfall. Conditions at this station are believed to be representative of conditions over large areas of the open waters of the Central Basin. The periods of observation included intensive sampling during the spring bloom periods of 1966, 1967, and 1975. Since the West Point discharge was initiated in November 1966, the intent of these studies was to assess whether there were any changes in phytoplankton standing stock and primary productivity after discharge of sewage effluent began.

A discriminant analysis applied to these data indicated that the years 1966 and 1967 could scarcely be distinguished, but that both were clearly distinguished from 1975. The year 1975 differed from 1966 and 1967 by having lower chlorophyll a concentrations and higher specific productivity. However, since nutrients are only very rarely limiting in Puget Sound, and even then for only very brief periods, differences between years in standing stock or productivity are not likely to reflect enrichment effects of sewage discharge. It is also difficult to interpret the meaning of a difference among years when only 3 years of data are analyzed. A significant difference could be attributed to natural year-to-year variation as easily as pointing to sewage effluents as the causal factor.

Ebbesmeyer and Helseth (1977) had a more comprehensive data set available to them (e.g., measurements of algal biomass and primary productivity at five stations between Elliott Bay and Point Jefferson, at either weekly or monthly intervals between 1966-1975). They were thus able to examine both spatial and temporal variations in biomass and productivity. They reported that there was a slight (although statistically insignificant) northward increase in both algal biomass and productivity from Elliott Bay to Point Jefferson. Although they interpreted this slight increase to be a result of the estuarine circulation pattern, it could also be associated with sewage inputs from West Point since the net circulation in the surface layer is northward. Ebbesmeyer and Helseth (1977) found no significant difference in the yearly variations of mean integrated primary productivity, but once again, annual means may obscure possible seasonal (or shorter term) differences attributable to sewage inputs. The available data suggest that the West Point discharge may be responsible for a slight increase (15-20 percent) in the extreme levels of integrated primary productivity in an area extending about 6.4-8 km (4-5 miles) north and south of the outfall. It should be emphasized that this possible increase is only in the extreme values; the data are inadequate for quantitative assessment of the contribution of the effluent's nutrients to the overall level of productivity throughout the Central Basin. Comparison of annual production figures for the pre- and post-discharge periods, however, reveals no major stimulation of algal growth for the main basin.

The analyses of Anderson (1976), Campbell et al. (1977), and Ebbesmeyer and Helseth (1977) assume that the primary effect of the West Point effluent on Puget Sound phytoplankton would be the stimulation of growth through nutrient addition; inhibition of primary production through the introduction of potentially-toxic chemical contaminants (which would tend to cancel out the former effect) has apparently not been considered. There are no data available to estimate the importance of such an effect.

While the West Point discharge is the largest existing municipal sewage discharge to Puget Sound, it would be of interest to examine the possible stimulation of phytoplankton primary

productivity by other smaller Puget Sound discharges, especially those with semi-enclosed, poorly flushing receiving waters. Unfortunately, studies of primary productivity in the vicinity of other municipal sewage discharges on Puget Sound have not been conducted. It would also be of interest to know what effect sewage discharges to Puget Sound may have on phytoplankton community composition. The only collections of phytoplankton for taxonomic analysis which have been conducted in the vicinity of municipal sewage discharges on Puget Sound were for three Tacoma discharges (Central, North End, Western Slopes). Unfortunately, the resulting data are so limited that virtually nothing can be concluded regarding possible effects of these discharges on phytoplankton community composition. Hence, there is no definitive information available on the possible effects of any municipal sewage discharge on Puget Sound phytoplankton community composition.

Metro sponsored two sampling programs (English 1976a; English and Thorne 1977) designed to assess possible impacts of the West Point discharge on zooplankton communities of the Central Basin. These included the analysis of ichthyoplankton caught in nets and acoustic observations of zooplankton concentrations in the immediate vicinity of the effluent plume. There was no analysis of zooplankton other than ichthyoplankton collected in the net samples. The first sampling program included the collection of samples at tri-weekly intervals over a 10-month period throughout the Central Basin, to identify patterns of seasonal and geographical distributions in the abundance of fish eggs and larvae. Fish eggs and larvae were also collected during the second sampling program, but in a smaller area from about 9.25 km (5.0 nmi) north of the West Point outfall to 12 km (6.5 nmi) south of the outfall. The sampling frequency was approximately monthly over a 13-month period. Acoustic observations were also made of zooplankton aggregations in the vicinity of the West Point effluent plume to determine whether there was any avoidance of the plume by these organisms.

The sampling programs of English (1976a) and English and Thorne (1977) are actually of very limited utility in attempting to analyze possible effects of the West Point discharge on either ichthyoplankton or zooplankton. Reasons for this conclusion include inadequate sampling in the immediate vicinity of the West Point outfall, failure to identify fish eggs beyond the generic level, lack of replicate samples (thus precluding rigorous statistical analysis of the data), and failure to identify zooplankton other than ichthyoplankton. The only statements that can be made regarding the impact of the West Point discharge on the ichthyoplankton community are that, qualitatively speaking, patterns of seasonal abundance of fish eggs in a broad area surrounding the West Point outfall did not appear markedly different from those in the Central Basin as a whole, and that acoustic observations did not suggest a large disturbance of organisms by the effluent plume. The organisms responsible for sonic scattering in the vicinity of the West

Point plume were not identified, however, and the statistical significance of either observation is unknown.

The only other sampling of zooplankton in the vicinity of municipal sewage discharges on Puget Sound was the collection of zooplankton near the three Tacoma discharges mentioned earlier. Unfortunately, as in the case of the phytoplankton sampling programs at these locations, the resulting data are so limited that virtually nothing can be concluded regarding possible effects of these discharges on zooplankton community composition. Hence, there is no definitive information available on the possible effects of any municipal sewage discharge to Puget Sound on the ecology of the zooplankton community.

FWPCA and WSPCC (1967) reported on the investigation of possible effects of the discharge of pulp and paper mill wastes on phytoplankton and zooplankton in Bellingham Bay and in Port Gardner (Everett). Sampling was conducted in each area at 4- to 8-week intervals over a 1-year period in 1964-1965. Ten stations were occupied in Bellingham Bay, while five stations were occupied in Port Gardner. At each station, zooplankton were collected in horizontal net tows, and phytoplankton were collected in water bottles. Preserved samples were analyzed for species composition of each community. Copepods were identified to species, other zooplankton were identified to broader taxonomic groups. Phytoplankton were only identified to genera. Other analyses included the measurement of chlorophyll concentrations to estimate phytoplankton biomass, and the measurement of simulated in situ primary productivity.

Despite the collection of samples during 10 cruises over a 1-year period, the data were averaged over these cruises for each station, and discussion of the data by FWPCA and WSPCC (1967) is limited to differences among stations in these annual mean values. This is a relatively insensitive method of analyzing these data; it may not be capable of detecting effects which are only apparent at one time of the year. Not surprisingly, it was reported that in each area there were no significant differences among stations in any of the following values: chlorophyll a concentration, phytoplankton concentration, number of phytoplankton taxa, zooplankton concentration, number of zooplankton taxa, and the percentage of adults making up the zooplankton. Furthermore, there was general agreement among stations in the dominant organisms in both the phytoplankton and zooplankton communities. The authors concluded that the structure of the plankton community was essentially the same throughout each study area.

The only significant difference observed among the stations in each study area was in the rate of primary productivity. In Bellingham Bay, the mean productivity was significantly lower at two stations than at any of the remaining eight, while in Port Gardner the mean productivity was significantly lower at one station than at any of the remaining four. In each area, the stations with these depressed productivity values were those

with the highest concentrations of sulfite waste liquor (SWL). Further analyses of the data revealed that depression of phytoplankton productivity apparently occurred at concentrations of SWL greater than 50 ppm, a value which was often exceeded in the northeastern quarter of Bellingham Bay and in the inner harbor at Everett. While a definite cause-and-effect relationship was not demonstrated between SWL and depressions in phytoplankton productivity, it did appear that the discharge of pulp and paper mill wastes in each area was adversely affecting the productivity of the phytoplankton community.

In a study of the possible effects of the discharge of metal plating wastes and other wastes from Keyport Navy Torpedo Station on the biological communities of Liberty Bay, Cummins et al. (1976) examined the abundance and species composition of phytoplankton at four locations. A dense phytoplankton bloom composed primarily of dinoflagellates (*Prorocentrum gracile* and *Gymnodinium splendens*) was found in the surface waters near the center of the bay. This bloom was attributed to the supply of nutrients entering the bay from Port Orchard and the slow flushing of the bay. It was deemed possible that the decomposition of the algal biomass produced during the spring phytoplankton bloom was primarily responsible for elevated ammonia concentrations which may have further stimulated phytoplankton growth. Cummins et al. (1976) also indicated, however, that ammonia and organic matter discharged to the bay by local sewage treatment plants "should also be considered as potentially important sources capable of supporting localized algal blooms." Their study did not attempt to assess the relative magnitude of the various nitrogen sources.

Chlorine is used as a disinfectant in municipal sewage and to prevent slime build-up in cooling water systems. Chlorine has been shown to inhibit photosynthesis by phytoplankton. Although no research has been conducted in Puget Sound, data collected elsewhere (Eppley et al. 1976) would indicate that inhibition of photosynthesis by chlorine is likely to occur in nearfield plumes from cooling water discharges.

Westley et al. (1975) analyzed both phytoplankton abundance (as chlorophyll *a* concentrations) and productivity (*in situ* measurements) in the vicinity of both the barge and pipeline disposal of dredge spoils from Olympia Harbor in order to ascertain whether such disposal operations had any adverse effects on phytoplankton. They did not, however, analyze the species composition of the phytoplankton community. The sediments of Olympia Harbor, although having a relatively high volatile solids content, had been judged to have only a moderate to low relative toxicity. Natural changes in phytoplankton abundance and productivity at the site of the barge disposal of dredge spoils masked any minor changes which might have been attributed to effects of the barge disposal operations. The pipeline dredging operation appeared to stimulate phytoplankton growth since both phytoplankton abundance and productivity were found to be higher in the most turbid part of the spoil plume than in

adjacent clear water areas. Such an effect might be attributed to the increased availability of nutrients to the phytoplankton, caused by the suspension of sediments high in organic content. Extrapolation from these results to other situations where dredge spoils are disposed of may not be appropriate if the character of the sediments is markedly different. Chemically-contaminated sediments (e.g., those from portions of the Duwamish River or from the Commencement Bay Waterways) might have very different effects than did these relatively innocuous sediments from Olympia Harbor.

Toxicity Bioassays

Plankton have been used in several ways to assess adverse effects of chemical contaminants in Puget Sound. The most extensive uses of plankton for this purpose have been bioassays utilizing the meroplanktonic larvae of the Pacific oyster (*Crassostrea gigas*). Similar studies have occurred on the Atlantic coast (Calabrese et al. 1973). Limited use has also been made of phytoplankton and zooplankton in bioassays to test for adverse effects of PCBs on these organisms, which are important components of Puget Sound communities.

Development of the bioassay techniques using the Pacific oyster has taken place for over 20 years, primarily by WDF. The bioassay was designed to provide a statistically-validated biological measure which could be readily applied to the problem of assessing the water quality of receiving waters subjected to a broad variety of pollutant inputs. The early development of this bioassay is reviewed by Woelke (1972), who also describes the procedures in considerable detail. Briefly, the bioassay involves innoculating a sample of the receiving water to be tested with a large number of newly-fertilized embryos of the Pacific oyster, holding this sample in a water bath at constant temperature for 48 hours, and allowing the embryos to develop into fully-shelled veligers. After this time, a subsample is preserved with formalin and examined under a microscope to assess the numbers of completely shelled (normal) and incompletely shelled (abnormal) larvae. Using a broad variety of pollutants, it has been shown that the percent of the larvae developing abnormally is a valid measure of the toxicity of the water sample containing the pollutant in question.

Extensive testing has shown that abnormal development of the oyster larvae occurs in response to a wide variety of chemical contaminants, and that for most of the contaminants tested, the oyster larvae are either as sensitive or more sensitive than other organisms used in bioassays. It has been shown (Woelke 1972) that, in general, the level of physical or chemical stress that causes an increase in the percent of abnormal development of the oyster larvae will also have an adverse effect on other stages of the oyster's life, on the larvae and older stages of other bivalves, and, in many cases, on fish, crustaceans, sea urchins, algae, and other forms of

marine life. It has also been shown (Woelke 1972) that, in general, levels of physical or chemical stress having little effect on the oyster larvae will not be toxic to other species of marine life (although there are important exceptions, notably some pesticides and insecticides). It is felt that the oyster larvae bioassay provides an important method for assessing compliance with water quality standards in addition to the more conventional parameters (e.g., temperature, pH, dissolved oxygen, etc.).

While the use of the receiving water bioassay with oyster larvae to characterize pollution *in situ* is analogous to live-box studies using other organisms (e.g., salmon fry; see the section on fish toxicity bioassays), it differs from the live-box studies in its ability to test hundreds of discrete samples at one time using thousands of test specimens while requiring only a small volume of sample. The oyster larvae bioassay also bridges a void in relating purely laboratory studies to the effects of pollutants *in situ* (Cardwell et al. 1979a). It measures the response of a critical life stage to toxicants which have undergone the complex interactions and changes in chemical form accompanying their introduction into seawater.

One important refinement of the oyster larvae bioassay was the addition of an assessment of percent survival to the aforementioned assessment of the percent abnormal development. Cardwell et al. (1979a) compared the response of Pacific oyster larvae to several toxicants to the responses of other organisms (e.g., the larvae of other bivalves, Pacific herring [*Clupea harengus*], Dungeness crab [*Cancer magister*], and spot shrimp [*Pandalus platyceros*]). Cardwell et al. (1979a) concluded that pollutant concentrations not causing acute effects on bivalve larvae should offer protection to other forms of marine life, but because in a few cases the oyster larvae were not as sensitive as the other species, the lack of acute effects on oyster larvae cannot be concluded to be unequivocal evidence of nontoxicity for marine life in general.

Cardwell et al. (1976) discussed the use of the oyster larvae receiving water bioassay for assessing the efficiency of pollution abatement procedures instituted at sulfite pulp mills in Port Angeles and Everett, and at an aluminum smelter and an oil refinery in Ferndale. Reductions in the BOD loading by pulp mills in both areas were associated with dramatic decreases in receiving water toxicity to oyster larvae. At Port Angeles, the receiving water toxicity was apparently nearly eliminated, while at Everett the area of receiving water causing at least 50 percent abnormal larval development decreased from more than 50 km^2 prior to wastewater treatment to 1 km^2 after an aggregate reduction of BOD loading of 67 percent. Cardwell et al. (1979a) cautioned, however, that results near Everett suggest that improvements in the water treatment processes may not always result in reductions in receiving water toxicity to oyster larvae. Near Ferndale, initial attempts to remove the fluorides

and particulates from the process effluent of the aluminum smelter by precipitation with polyelectrolytes was shown to be of limited merit for reducing either total effluent loading of these substances or receiving water toxicity to oyster larvae. Subsequent neutralization of the highly acid effluent and recovery of the contaminants by filtering stack emissions through felt bags not only reduced effluent loading substantially, but also ameliorated both effluent and receiving water toxicity to oyster larvae. Although the oil refinery was found to have only a limited effect on receiving water toxicity, the installation of additional secondary waste treatment facilities appeared to mitigate this effect. While reductions in receiving water toxicity are clearly associated with reductions in waste loading, attempts to establish a causal relationship between these events were inconclusive (Cardwell et al. 1979a).

In addition to the investigation of water quality in the vicinity of pulp mills, an aluminum smelter, and an oil refinery, oyster larvae bioassays have been used in a variety of other ways to investigate problems with the quality of the receiving water environment in various locations around Puget Sound. It is not necessary here to describe all of these uses of the oyster larvae bioassays, but a few representative uses will be discussed briefly to demonstrate the adaptability of these procedures.

Westley et al. (1975) utilized oyster larvae bioassays as one method of assessing the environmental impact of dredging and dredge spoil disposal operations in Southern Puget Sound. Some problems were encountered in applying the oyster larvae bioassay to an investigation of the effects of the actual clamshell and pipeline dredging operations in the vicinity of Olympia Harbor and Budd Inlet. Even before the start of the dredging, high mortalities of the larvae occurred, and this condition persisted throughout the dredging operation. It became apparent that unknown properties of the water in this area were inimical to Pacific oyster embryos, and that in the presence of such high mortalities, it was impossible to detect adverse effects of the dredging operations. The oyster larvae bioassay was applied successfully to an assessment of the effects of the barge dumping of dredge spoils in Dana Passage, where little mortality or abnormal development was detected, suggesting that this method of dredge spoil disposal is not harmful to the developing oyster larvae.

Cardwell et al. (1979b) used the oyster larvae bioassays to investigate the problem of persistent and recurrent toxicity of the waters of Southern Puget Sound to adult oysters. The bioassays were used to assess the toxicity of the receiving waters, of the effluent from sewage treatment plants, of laboratory cultures of dinoflagellates, and of alterations in the salinity and ammonia content of the water. The results clearly implicate blooms of the dinoflagellates *Ceratium fusus* and *Gymnodinium splendens* as the causes of the observed mortalities of the Pacific oyster larvae in these bioassays. It is therefore

assumed that blooms of these dinoflagellates, known to occur in Southern Puget Sound, are responsible for the mass mortalities of adult Pacific oysters, and that they may contribute to the reduced reproductive success and viability of the native Olympia oyster.

In an investigation of possible causes of mortalities of Pacific oyster embryos and larvae at a hatchery on Liberty Bay, Cummins et al. (1976) made use of the oyster larvae bioassay techniques to assess the toxicity of the receiving waters of Liberty Bay, of the bay's sediments, and of the effluent from several local sewage treatment plants. Survival of the oyster larvae was relatively high and the percent abnormal development of the larvae was relatively low in the water samples from all stations in the bay except in those from the vicinity of a dense algal bloom. This algal bloom was composed primarily of the dinoflagellates Prorocentrum gracile and Gymnodinium splendens. The adverse effects of the Liberty Bay sediments on the oyster larvae were demonstrated to be relatively minor, suggesting that these sediments were not contaminated with acutely toxic substances. The concentration of sewage treatment plant effluent resulting in 50 percent mortality of oyster larvae was estimated to range between 25 and >200 ml/l for the three plants tested, while the concentration of effluent resulting in 50 percent larval abnormality was estimated to range between 20-140 ml/l. Crude estimates of the effluent dilution to be expected from each of these discharges suggest that only the effluent from the Poulsbo sewage treatment plant could have been responsible for the observed mortalities at the hatchery site, although even this determination is subject to some uncertainty. Cummins et al. (1976) concluded that the most likely cause of the observed oyster larvae mortalities at the hatchery was the presence of high concentrations of dinoflagellates in the waters of Liberty Bay. The fact that one of the abundant dinoflagellates, Gymnodinium splendens, was the same species implicated in the mortalities of adult and larval oysters in Southern Puget Sound (Cardwell et al. 1979b) lends credence to this conclusion.

Pavlou and Dexter (1977) utilized a variety of laboratory experiments to assess both toxic and sublethal effects of PCBs on representative phytoplankton and zooplankton species from Puget Sound. Two basic types of stress response functions were measured for phytoplankton (two species of diatoms): 1) alterations in growth characteristics (measured by monitoring cell density or biomass density), and 2) changes in the activity of specific enzymatic or metabolic systems (processes measured included nutrient uptake, electron transport system [ETS] activity, and glutamate dehydrogenase [GDH] activity). These studies were performed in both static reactors (batch cultures) and continuous flow systems (chemostats). For zooplankton (one species of copepod), the respiration rate was measured to establish toxicity threshold values, and observations were made of both dead and moribund individuals.

Pavlou and Dexter's (1977) results are in general agreement with established literature data on the effects of PCBs on plankton. An acute toxicity threshold of approximately 10 ppb was found for both phytoplankton and zooplankton, with more subtle effects on phytoplankton nutrient uptake and GDH activity occurring at an order of magnitude lower concentrations. These concentrations were then compared with ambient levels of PCBs measured in Puget Sound. Even for the most toxic compound, the environmental levels were approximately two orders of magnitude below the toxicity thresholds. They caution, however, that the ambiguity of the available data does not justify establishing an absolute "safe" level for these compounds. Since the toxicity thresholds are above the solubility of these compounds, adsorption may take place on the surface of these organisms, thus resulting in greater exposure than would be predicted by equilibrium partitioning. Additional problems in extrapolating these laboratory data to the field include the failure to consider possible synergistic effects of other natural or anthropogenic stresses, and the different sensitivity of other phytoplankton and/or zooplankton species. Finally, although the results of this and other studies are often given in terms of "total PCBs", the toxicity may be due to only one or a few components of that mixture, and thus the threshold concentrations of that component may be lower than that of the total mixture.

Rosenthal and Alderdice (1976) reviewed the literature on the sublethal effects of pollutants on marine fish eggs and larvae. The presence of some heavy metals or other pollutants blocked fertilization or embryonic and larval development. Longwell (1977) found similar effects in the presence of oil. Sindermann (1979) noted that experimental exposure to sulfuric acid and to certain algicides found in pulp mill effluent resulted in abnormal embryos and larvae of Atlantic herring. During his review, Sindermann (1979) also noted that a number of heavy metals, pesticides, and polycyclic aromatic hydrocarbons have been shown to be mutagenic or toxic in fish gametes, embryos, larvae, and juveniles, e.g., fish eggs in 1 ppm cadmium produced few larvae.

Sublethal effects of certain insecticides have been noted for mysid shrimp. Nimmo et al. (1981) found that dimilin (a benzoylphenyl urea) and EPN (an organophosphate) adversely affect reproductive success of a mysid. Dimilin showed a gradual effect with dose, whereas EPN showed a strong threshold effect with dose. Two organophosphate insecticides (methyl parathion and phorate) adversely impacted mysid swimming speed after 96 hours of exposure. Threshold effect concentrations were low (0.31-0.58 ppb and 0.078-0.18 ppb, respectively). Effect and no effect concentrations were very similar to those observed in 28-day life cycle tests.

Bioaccumulation

Relative to other biotic groups, there have been relatively few attempts to examine the bioaccumulation of chemical contaminants in the plankton of Puget Sound. Limited analyses have been conducted of the concentrations of certain trace metals in zooplankton collected from a number of locations in the Sound, but there are no data available on the concentrations of trace metals in phytoplankton. Similarly, there have been only a very limited number of analyses of PCBs in the zooplankton of the Sound, and none which examined the concentrations of PCBs in phytoplankton. No studies could be located which examined the concentrations of organic contaminants other than PCBs in Puget Sound plankton.

Schell et al. (1976, 1977) analyzed trace metal concentrations in zooplankton collected in net hauls at various locations throughout Puget Sound. There is no indication that any effort was made to separate zooplankton from all other particulate matter, however, so the reported metal concentrations may represent the concentrations in the total particulate matter retained by the net. Sampling was initially conducted in September 1974 between Shilshole Bay and Carkeek Park as well as off West Point. These samples were analyzed for the concentrations of cadmium, copper, lead, mercury, and zinc. Sampling was conducted in March 1975 at four locations (near West Point, Alki Point, Point No Point, and the 4-mile dump site off Magnolia), and in July 1975 in Hood Canal. West Point, Alki Point, and Carkeek Park all represent areas with sewage outfalls; the 4-mile dump site represents the site where dredged sediments from the Duwamish River are dumped. The samples collected at Point No Point and in Hood Canal were intended to serve as background stations. The 1975 samples were analyzed for the concentrations of antimony, cadmium, chromium, cobalt, copper, lead, selenium, and zinc.

With the exceptions of cadmium and selenium, the highest concentrations of all of the metals analyzed by Schell et al. (1976, 1977) were found in the plankton samples collected in the vicinity of the 4-mile dump site. While Schell et al. (1976) indicated that there were "no significant differences" in the concentrations of cadmium, chromium, and selenium at Point No Point and 4-mile dump site, there is no indication that replicate samples were taken and no discussion of statistical tests being applied to the data. Hence, this conclusion is subject to some uncertainty. Among the remaining metals, there were rather large differences between the concentrations observed in plankton at the 4-mile dump site and those at Point No Point (antimony, 50.2 vs. 0.33 ppm dry weight; cobalt, 1.72 vs. 0.63 ppm dry weight; copper, 189.8 vs. 57.1 ppm dry weight; lead [reported by Schell et al. 1976 as 589.6 ppm dry weight, but by Schell et al. 1977 as 885.6 ppm dry weight] vs. 17.8 ppm dry weight; and zinc, 337 vs. 95.2 ppm dry weight). Schell et al. (1976, 1977) speculate that these high metal concentrations in the plankton near this dump site may be due either to parti-

culate matter contaminated with metals adhering to the plankton or to ingestion of this particulate matter by the plankton. Due to the lack of replicate samples and a statistical analysis of the data, it is impossible to determine whether the metals concentrations were elevated in plankton collected near the sewage outfalls. Further study is certainly suggested since some of the metal concentrations reported for the plankton near the dump site are exceedingly high.

There have been a few attempts to measure the concentrations of PCBs in zooplankton from different areas of Puget Sound (Clayton 1975; Clayton et al. 1977; Pavlou and Dexter 1977, 1979). Mixed zooplankton samples were collected in the Central Basin, Elliott Bay, Whidbey Basin, Sinclair Inlet, Hood Canal, Admiralty Inlet, and the Strait of Juan de Fuca. As in the case of Schell et al. (1976, 1977), there is no indication that zooplankton were separated from other particulate matter, so the reported metals concentrations may represent the concentrations for all particulate matter retained by the net. Variations in the concentrations of PCBs in the zooplankton from these areas may reflect not only differences in the ambient seawater concentrations which the organisms were exposed to, but also species-specific physiological differences since the zooplankton samples contained different combinations of species. An important difference of this nature is the amount of lipid in the organisms, which may vary either with species or with season. Clayton (1975 in Dexter et al. 1981) has shown, for example, that while the mean concentration of PCBs on a wet weight basis for zooplankton collected in the Whidbey Basin varied considerably between a November collection and a July collection (0.288 ppm wet weight vs. 0.031 ppm wet weight), the concentrations were actually more similar when reported on a lipid weight basis (4.44 ppm lipid weight vs. 2.69 ppm lipid weight). The zooplankton collected in November had a mean lipid content of 6.6 percent, while those collected in July had a mean lipid content of only 1.1 percent. Hence, for comparative purposes, it is probably best to report the concentrations of PCBs in zooplankton on a lipid weight basis. On this basis, the concentrations of PCBs in the zooplankton from the various areas listed above ranged between 1-16 ppm lipid weight (Clayton et al. 1977). The highest concentration was found in zooplankton from Sinclair Inlet, while the lowest concentrations were found in Hood Canal, the Strait of Juan de Fuca, and Admiralty Inlet. The remaining areas (i.e., the Central Basin, Whidbey Basin, and Elliott Bay) had intermediate concentrations.

Clayton et al. (1977) have shown that the concentrations of PCBs in zooplankton (on a lipid weight basis) are primarily a function of the concentration of PCBs in the water from which the zooplankton were collected. This suggests that the accumulation of PCBs in zooplankton is primarily the result of equilibrium partitioning of these compounds between the organisms and seawater, and not a result of other mechanisms (e.g., ingestion of PCB-contaminated particulates by the zooplankton). The accumulation of PCBs may be viewed as a balance between the

intake rate, the storage capacity of the organism, and the elimination rate (Dexter et al. 1981). For small organisms such as zooplankton, with a high surface area-to-volume ratio, the PCB residues are capable of facile exchange between the surrounding water and the internal sorption sites, primarily lipids. Although PCB residues may be accumulated from the food, this facile exchange mechanism results in a rapid equilibration of the concentrations in the organism with the concentrations in the surrounding water. Hence, the ultimate body burden of PCBs in zooplankton reflects a partitioning of the residues between the lipid and water phases (Dexter et al. 1981). Clayton et al. (1977) suggest that if this relationship is strong enough (admittedly, more data should be collected to validate this hypothesis), the concentrations of PCBs in zooplankton might be used as indicators of the PCB concentrations in seawater, which are usually very low and difficult to measure.

Clayton et al. (1977) note that a similar equilibrium partitioning mechanism may be applicable to fish as well, despite their smaller surface area-to-volume ratio, due to rapid exchange across the gill surfaces and subsequent transport to and from internal lipid pools via the circulatory system. Accumulation of PCBs by equilibrium partitioning may not be applicable to marine mammals, however, since they possess no equivalent external surface for exchange. For mammals, the primary mechanism for uptake of PCBs is likely through the food, and since elimination of PCBs through excreta is relatively inefficient, PCBs may be expected to accumulate with time in the bodies of mammals (Dexter et al. 1981).

Paralytic Shellfish Poisoning

Paralytic shellfish poisoning (PSP) is a dangerous condition which results when humans eat marine organisms (especially bivalve molluscs, e.g., clams, mussels, oysters) which have ingested large numbers of certain species of dinoflagellates. From 1971-1977, 12 outbreaks and 68 cases of PSP were reported in the United States (Hughes 1979). These dinoflagellates produce a chemical which is acutely toxic to humans when it is concentrated in the bodies of these filter-feeding organisms. The toxicity of these organisms is primarily of concern when the dinoflagellates have been present in excessively large concentrations commonly referred to as "red tides." PSP in the Puget Sound area is associated with blooms of the dinoflagellate *Gonyaulax catenella*, and although other dinoflagellate species in this area can bloom to the point where they impart a red color to the water, they do not apparently produce a toxin associated with PSP.

Work by Wall (1975), Dale (1977), and Turpin et al. (1978) support the hypothesis that blooms may be initiated by benthic resting cysts. Field observations and laboratory research by Anderson and Morel (1978) shed light on the key environmental

factors effecting spring and fall cyst germination and emergence. Of the four parameters studied (nutrients, salinity, rainfall, and temperature), only seasonal temperature changes correlated with two blooms. Laboratory experiments supported the theory that spring blooms begin in response to warming waters, and initiation of fall blooms depend on the cooling of elevated summer water temperatures; but viability, referred to as the ability of a germinated cyst to become motile, depends on light and trace element availability.

Nuisance blooms of Gonyaulax catenella have not historically been a problem in the Central Basin, although they had occurred frequently in the Strait of Juan de Fuca and in the coastal waters of British Columbia. In recent years, however, G. catenella has become abundant enough to cause PSP in the Central Basin. In 1978, there was an outbreak of red tide in Penn Cove, on the east side of Whidbey Island, which was caused by excessive growth of G. catenella (Norris-Nishitani et al. 1979; Nishitani and Chew 1979). Mussels collected in October 1978 in Penn Cove had extremely high levels of PSP toxin, far exceeding the allowable level of 80 μg toxin/100 g shellfish meat (Norris-Nishitani et al. 1979). This red tide appeared to originate in the area around Penn Cove and Holmes Harbor and then spread southward (Chew pers. comm.). Although red tides have continued to occur in Puget Sound waters in the years following 1978, it is no longer believed that the red tides originate in the Penn Cove-Holmes Harbor area. The entire Central Basin is now "seeded" with G. catenella cysts, and a bloom can originate anywhere (Chew pers. comm.). In 1979, mussels containing PSP toxin in concentrations exceeding the allowable limit were found throughout the Central Basin (Nishitani and Chew 1979).

Nutrients, Trace Metals, and Upwelling. Although a link between sewage discharges and the occurrence of red tides has been suggested for other areas (Doig and Martin 1974), a cause-and-effect relationship between the two has not been identified in the Puget Sound region (Chew pers. comm.). Sewage discharges might affect the growth of red tide organisms in several different ways. There is concern, for instance, that the introduction of sewage nutrients may have an effect on the peak algal biomass attained during a bloom of dinoflagellates, although this does not appear likely since algal growth in Puget Sound is generally controlled by stability of the water column, estuarine flushing, and the light environment (Winter et al. 1975). Of perhaps greater concern is the possibility that alterations in the nutrient environment (e.g., changes in the relative concentrations of nitrate and ammonia) caused by the discharge of sewage effluent might promote the growth of G. catenella over other phytoplankton species. Also, although no relationship has been demonstrated to date, it is possible that some factor (e.g., trace metals) introduced to the Sound either through municipal or industrial discharges might in some way be responsible for initiation of blooms of G. catenella. Further

study will be required to determine whether there is, in fact, any relationship between anthropogenic perturbations to the Puget Sound environment and the growth of these red tide organisms.

One of the most well documented environmental conditions associated with dinoflagellate blooms is the occurrence of upwelling. This upward, vertical flow of deep water brings nutrients to the surface layers. Early studies by Hutner and McLaughlin (1958) and more recently Blasco (1975) and Sorokin and Kogelschatz (1979) have shown that blooms of dinoflagellates often occur in areas of upwelling. However wind-driven upwelling can also prevent the accumulation of dinoflagellates on the surface by creating strong currents that restrict their mobility (Provasoli 1979).

Since red tides are largely coastal, it has been suggested that terrestrial runoff rich in phosphates (Bold and Wynne 1978), humic acids (Prakash and Rashid 1968), and to some extent, vitamin B_{12} (Stewart et al. 1966), can induce these phytoplankton blooms. Rain-generated runoff may also reduce saline concentrations in marine coastal waters, and thereby promote dinoflagellate blooms (Bold and Wynne 1978). Prakash and Rashid (1968) have found that some toxic dinoflagellate species prefer saline solutions less concentrated than usual marine salinities.

Research has indicated that "preconditioning" of waters by previous algal biological activity such as diatom blooms may promote subsequent dinoflagellate population explosions by concentrating nutrients, or by decreasing certain nutrients which are holding their numbers in check (Takauji 1981). Organic secretions of nondinoflagellate species may also "condition" waters through complexing toxic trace metal ions such as copper (McKnight and Morel 1979).

Trophic Effects

Almost all the studies that have been conducted to try to document cause-and-effect relationships between pollutants and changes in the biota have examined only one particular aspect of the biota, e.g., fish, plankton or benthic communities. No work has been done in Puget Sound to examine the effects of pollutants on simple food chains.

Stirling (1974 *in* Steele 1979) examined the effects of copper and mercury on a simple food chain, phytoplankton-*Tellina tenuis*-plaice, in British waters. Copper demonstrated adverse effects on all three species, and the deleterious effects were augmented at the second and third level by food chain interactions. It was noted, however, that deleterious effects of mercury on the food supply of the clam were offset by reduced predation pressure resulting from adverse effects of

mercury on plaice. This rather simple experiment demonstrates the difficulty in documenting cause-and-effect relationships in complex natural communities.

Marine Birds, Marine Mammals, and Human Health

NOAA is currently sponsoring studies on accumulated levels of xenobiotics and heavy metals in marine birds and mammals of Puget Sound. The study on contaminants in marine birds is near completion, and the preliminary results indicate that some birds, especially from Commencement Bay have high levels of PCBs relative to values reported in the literature (Long pers. comm.). The highest levels were 80 ppm in adipose tissue from heron taken near Tacoma. Values were lower in birds taken from the Seattle area and Protection Island/Sequim Bay. There were significant differences in cadmium, lead, and mercury concentrations in tissues between the two urban and two reference sites, but no clear pattern in the differences. Surprisingly, the only organic contaminants detected were PCB and traces of DDE. A second study is planned by NOAA to determine whether there is evidence that observed levels in bird tissues are associated with deleterious effects.

Arndt (1973) conducted a study of DDT and PCB levels in three seal populations: one in northern Puget Sound, one in Southern Puget Sound, and a third in Grays Harbor. Of the three populations, only PCB levels in the Southern Puget Sound population were significantly higher than in the other two, and these levels were much higher than previously recorded in pinniped populations. The Southern Puget Sound population also displayed a high rate of spontaneous abortions and birth defects. Preliminary data from the recent NOAA study are not yet available (Long pers. comm.).

No studies have been conducted to determine the impact on human health following ingestion of diseased or contaminated fish from urbanized areas of Puget Sound. Two specific human diseases have been attributed to pollutants: excessive cadmium in drinking water led to the occurrence of itai-itai disease in an area of Japan (Kobayashi 1971) and ingestion of seafood or seed contaminated or treated with mercury compounds has been known to cause Minamata disease (Irukayama 1967).

Carcinogenic, mutagenic, and teratogenic properties of many organic compounds are known or suspected at moderate to high dosages, but little is understood about these properties at low dosages. Major concern has been focused in the past on compounds known to bioaccumulate (e.g., PCBs) in body tissues because of known or suspected adverse effects on human health.

Summary

Fish

Investigations of the ecology of fish communities in Puget Sound have failed to indicate any substantial adverse impacts of municipal waste discharge on species composition, abundance, or diversity. The available data suggest that in the vicinity of Seattle's West Point sewage outfall, there may be some increased abundances of demersal fishes, and there may be relatively minor alterations in species composition of this community which might be caused by the discharge of sewage effluent. Other differences noted at West Point may be attributed to natural habitat differences rather than to sewage discharge. Studies of the ecology of fish communities in the vicinity of other municipal sewage effluent discharges on Puget Sound are inappropriate for demonstrating effects on fish communities.

Extensive studies conducted in the vicinity of several pulp and paper mills in the mid-1960s demonstrated that the mills were often located adjacent to important nursery areas for both anadromous and marine fish species. In addition, it was apparent that the effluent from these mills was often highly toxic to juvenile fishes, and that the ecological implications of these industrial discharges were therefore potentially very important. Since that time, there have been dramatic reductions in the pollutant discharges from these mills, as they were forced to either institute more advanced treatment measures or shift to other processing methods. Follow-up studies have been conducted in Port Gardner as part of the ECOBAM program, but the results have not yet been released.

The Puget Sound region has two heavily-industrialized urban estuaries: the Duwamish River-Elliott Bay system in Seattle, and the Puyallup River-Commencement Bay system in Tacoma. Both are known to have received large quantities of toxic chemicals over the years, and several studies have attempted to examine the effects that industrialization and chemical contamination of these areas have had on the resident fish communities. Detailed comparisons have not been made, however, between the fish communities of the urban, industrialized estuaries and those of undeveloped, nonindustrialized estuaries (e.g., the Nisqually River Delta), so it is difficult to describe accurately how the fish communities of the urban estuaries may have been altered by industrial activities. Malins et al. (1982a) found that the abundance of some fish species (as indicated by the catch per unit effort) was negatively correlated with the distributions of some toxicants in the sediments of these estuaries. While such correlations are suggestive of cause-and-effect relationships between the fish distributions and the concentrations of chemical contaminants, far more detailed studies will have to be conducted before it is known what factor ultimately influences the abundance of these and other fish species.

It is of interest to know what effect the disposal of dredge spoils (especially chemically-contaminated dredge spoils from the urban estuaries) might have on fish populations, but the limited studies conducted to date do not permit definitive conclusions. Studies of such relationships must be relatively extensive in order to discriminate natural population fluctuations from dredge spoil disposal effects, and such extensive sampling has not been conducted at any disposal area in Puget Sound.

Laboratory toxicity bioassays with fishes have been conducted using sediments and sewage treatment plant effluents. Effluent bioassays can be used as an indication of relative toxicity under controlled conditions. Toxic constituent concentrations can also be measured throughout the exposure period. Their major limitation is that they do not enable an assessment of the interactive or cumulative effects of the numerous pollutant sources that exist in many industrialized areas of Puget Sound. Existing data indicate that lethal toxicity of municipal effluent is a function of sewage treatment technology and periodic releases of "slugs" of toxicants. Studies on toxic effects of dredge spoil activities are limited by site-specific conditions.

In situ bioassays with fishes have been used in the Puget Sound area near pulp and paper mill effluents and near dredging operations. The results of such studies can be confounded by the lack of available water quality information at the exposure site and high mortalities in control cages. Such studies are valuable, however, in assessing relative changes in toxicity (i.e., water quality), either in a spatial or temporal context. For example, previous *in situ* studies have demonstrated that acute toxicity can occur in salmonids exposed to pulp and paper mill discharges. Continuing use of this technique coudl potentially serve to examine the change in ambient toxicity associated with improvements in effluent treatment.

While there have been numerous investigations of the concentrations of metals in the tissues of various fish species from Puget Sound, there have been few, if any, definitive results which conclusively demonstrate the accumulation of metals in these tissues in excess of "normal" or "background" concentrations. Although virtually all of the metals examined exist in detectable concentrations in the tissues of the fishes, the general conclusion is that it is not known whether the reported concentrations are in excess of background concentrations for fishes in relatively "unpolluted" waters. Several reasons can be cited for this lack of conclusive evidence of the existence or absence of significant bioaccumulation of metals. First and foremost is the fact that none of the studies to date has included sufficient numbers of replicate samples to allow statistical analysis of the data. In the absence of sufficient replicates, it is impossible to judge whether an apparent difference in the tissue concentrations of a given metal in the fish from two different areas is statistically significant or

whether observed differences simply reflect natural variation. Studies completed to date have utilized a wide variety of fish species, and virtually nothing is known about species-specific susceptibility to the bioaccumulation of metals. The available evidence suggestive of bioaccumulation is primarily for demersal fish species, while pelagic fish species are apparently less prone to bioaccumulate metals. Many of the past studies have often suffered from the lack of fish samples collected from an appropriate control area. While it is often difficult to select a control area having characteristics similar to those in a polluted area except for the presence of chemical contaminants, past studies have often included no control area at all or an area whose "unpolluted" status is either assumed or poorly documented.

Available data on the concentrations of PCBs in fishes of Puget Sound (and similarly for most other organic contaminants) suffer from many of the same problems found with data on the concentrations of metals in fishes (e.g., lack of adequate replication, differences in fish species analyzed, lack of appropriate controls). Nevertheless, these data are more suggestive of significant bioaccumulation because the differences in the concentrations of these compounds between fish in known polluted areas and those in background or control areas are much larger than are the usual differences in metals concentrations between two such areas. Whereas metals concentrations often only differ by two- or three-fold between fish in polluted urban areas and those in presumed control areas, the concentrations of PCBs in fish from two such areas often differ by one or two (or even more) orders of magnitude. The available evidence suggests that accumulation of PCBs is most pronounced in demersal fishes (e.g., English sole, rock sole, sculpins) inhabiting urban estuaries (e.g., Commencement Bay, Elliott Bay, Duwamish River) known to have sediments contaminated with high concentrations of these compounds.

There have been very few studies of the concentrations of organic contaminants other than PCBs in the tissues of fishes from Puget Sound. The limited data available suggest that chlorinated butadienes are found in consistently high concentrations in fish from the Hylebos Waterway in Tacoma but nowhere else, while chlorinated hydrocarbon pesticides and hexachlorobenzene are found in high concentrations in fish not only from the Hylebos Waterway by also from the Duwamish River and the Seattle Waterfront. Polynuclear aromatic hydrocarbons are generally present only in low concentrations in the livers of fishes from all areas of Puget Sound. This reflects the fact that fish are apparently able to metabolize these compounds. They are, however, present in slightly higher concentrations in fish from Elliott and Commencement Bays. Correlations between the body burdens of virtually all of the organic chemical contaminants and known sources of these compounds are best for the demersal fishes, and not well developed for semi-pelagic or pelagic species.

The mechanisms of bioaccumulation of organic contaminants are not known at this time. It is not known, for instance, whether the primary pathway into the bodies of the fishes is via ingestion or contaminated prey organisms, uptake through the gills, or direct uptake through the skin. There is a limited amount of data that suggest uptake of PCB does not result from exposure to PCB in the water column. The consequences to fishes, if any, that result from accumulation of these substances are also largely unknown.

Numerous studies of pathological conditions among fishes of Puget Sound have revealed several consistent relationships: the conditions often occur in higher prevalence in areas known to be contaminated by a diversity of chemicals, they appear to affect demersal fish species (e.g., flounder and sole) more often than pelagic fish species (e.g., salmon), and their etiology is largely unknown. Fin erosion disease, while not confined to polluted, urban areas, is more prevalent in such areas, suggesting that the condition is in some way caused by exposure to chemical contaminants. While certain evidence from lab exposures and field studies suggests that chemical contamination may be involved in the initiation of this disease, it is entirely possible that a combination of factors (e.g., chemical contamination, mechanical injury, physical factors) act in concert to bring about fin erosion. The distribution of skin tumor prevalence basically follows that of fin erosion; it is more common in areas with chemically-contaminated sediments than in less polluted areas. However, the association of skin tumors with contaminated environments is even more tenuous than the incidence of fin erosion. While the consequences of fin erosion for the individual fish are unknown, there are indications that skin tumors may be eventually fatal to fishes. It has been established, for instance, that the prevalence of tumor-bearing fish decreases with increasing age of the fish, suggesting that tumor-bearing fish disappear from the populations more rapidly than do normal fish. As is the case with fin erosion, it is entirely possible that multiple factors act either independently or synergistically to cause skin tumors.

Hepatomas and other liver abnormalities clearly occur much more frequently in demersal fishes from industrialized, urban estuaries than in less polluted areas of Puget Sound. Circumstantial evidence once again points to chemical contaminants as an important factor in the induction of these conditions.

For the other pathological abnormalities observed among fishes of Puget Sound, there have been relatively few detailed studies. Since these conditions occur at relatively low frequencies, much more extensive studies would be required to demonstrate any relationship between the distribution of these conditions and the distribution of known areas of chemical contamination.

Whereas there is a good evidence of an association between the occurrence of pathological conditions in demersal fishes and

the sites of intense industrial activity, the prevalence of fish disease does not appear markedly higher in the vicinity of large municipal sewage discharges, such as West Point, than in other similar areas without municipal sewage discharges. One possible hypothesis is that these pathological conditions are a function of some factor present in industrial wastes, but absent, or in considerably lower concentration, in municipal sewage effluents. An alternative hypothesis is that municipal sewage discharges are deliberately sited in areas of high flushing where fine suspended particulates are unlikely to settle, and therefore, initiation of toxic conditions is minimized.

It is a relatively straightforward proposition to sample the fishes in polluted and unpolluted areas of Puget Sound, to examine them for a variety of pathological conditions, and to assign percent prevalences of each condition to the respective areas. Given sufficiently large sample sizes, it is possible to demonstrate that statistically-significant differences occur in the prevalences of these conditions in the various areas, and that some of the conditions are most prevalent in the most contaminated areas.

Beyond simply documenting the existence of fish disease in various areas of Puget Sound, there have been relatively few attempts to investigate the causes of the observed pathological conditions. There are similarities between certain of these conditions occurring naturally in the fishes of Puget Sound and those induced in laboratory animals by exposure to a variety of chemical pollutants. There are interesting statistical correlations between the distribution of fish with certain of these conditions and the distribution of groups of chemical contaminants. This does not imply cause-and-effect, however, since it is still not known whether one chemical acting independently, or several acting synergistically, or even an as yet unmeasured chemical which happened to be correlated with the other chemicals, was/were the causal factor(s). Measurements of the concentrations of chemical contaminants in the tissues of fish with specific pathological conditions, as well as in the tissues of healthy fishes, have been performed on too few specimens to provide statistically-significant correlations which might indicate what chemicals cause these conditions.

Laboratory experiments designed to attempt to induce certain pathological conditions in fish by exposing them to chemically-contaminated sediments or by injecting them with extracts of those sediments have failed to reproduce those conditions observed in natural fishes from contaminated areas. The prospect of testing individually all or even a large fraction of the total array of chemical contaminants known to occur in such sediments is overwhelming, while testing the likelihood of synergistic effects among all of the possible combinations of those chemicals is virtually impossible.

Benthic Macroinvertebrates

Investigations of the ecology of benthic communities near pollutant sources have documented responses associated with changes in community structure and with changes in abundances of selected species. Although only on study examined the effects of dredged material disposal on benthos, the immediate effects and subsequent recovery were well documented. Studies of benthic communities in many industrialized embayments and nonindustrial areas in Puget Sound have not resulted in definitive conclusions on the possible modifications of benthic communities in areas of known sediment contamination.

Several studies of benthic macroinvertebrate assemblages near sewage discharges in Puget Sound have been conducted in support of applications for waivers from secondary treatment requirements. Biological effects at the largest single sewage discharge in Puget Sound (West Point) were associated with reduced total abundances and reduced abundances of some taxa in areas near the discharge. Although the causative agent(s) for the observed effects is unclear, recent evaluation of the infaunal data suggests that the local subtidal benthic communities may be responding to contaminated particulates. Comprehensive studies of intertidal floral and faunal assemblages near West Point and other areas of central Puget Sound receiving sewage discharges indicated that the only apparent effect was associated with modification of algal communities near West Point.

No definitive effects of smaller municipal sewage discharges have been documented at other sites in Puget Sound. These results may be due in part to the limited nature (e.g., few samples) of most of the studies. However, many of the smaller municipal discharges are located in erosional environments where high currents prevent sewage solids from accumulating near the outfalls. Thus, potential effects on the benthos are minimal at such sites.

Effects of pulp and paper mill discharges on subtidal benthos have been documented at several Puget Sound sites. The effects ranged from almost complete absence of macrofaunal benthos in inner harbor areas near the discharges to moderate changes in community structure at sites farther from the discharges. The reviewed studies were conducted during periods when pulp and paper mill discharges were considerably greater than at present, or when the magnitude of those discharges was just being reduced. Thus, the actual degree of recovery that may have occurred is unknown. Data from European waters (Pearson and Rosenberg 1978) indicate that recovery is possible in as little as 3 years, and present a potentially useful indicator of environmental stress on the benthic community.

Several studies have been conducted to determine the toxicity of Puget Sound sediments to benthic organisms. Amphipods have been the major test organisms used; however, tests have also been conducted on oligochaetes, polychaetes, several

bivalve mollusc species, and decapod crustaceans. The results have indicated that sediments in the industrialized areas of Puget Sound are toxic to many of the species tested. Specific results are dependent upon test species used and exposure apparatus/procedure. In one case (Swartz et al. 1982) the bioassay results were related to observed distributional characteristics of infaunal species (i.e., absence of amphipods from areas with toxic sediments). Perhaps the most interesting outcome of these bioassay results is the observation that sediment toxicity is very localized, suggesting that sediment contamination is also very patchy. More than one investigator has noted that sediment samples taken in the same general area show noticeably different toxic effects. These data suggest that sediment toxicity bioassays should incorporate a sampling design that accounts for highly localized distribution of contaminants.

The primary limitation of the sediment bioassays is the general absence of two kinds of information:

- Biological characteristics of indigenous benthic communities at the site of sample collection.
- Chemical analyses of sediment contaminants.

The previously conducted bioassays have served primarily to identify areas of potentially toxic sediments in the Puget Sound region. The causative agent(s) or the actual effects on indigenous organisms are presently unknown.

Surveys of bioaccumulation of metals in benthic organisms indicate that higher tissue levels of several metals are found near Seattle. There is also evidence of elevated levels of some metals in mussels in Commencement Bay. However, the studies of bioaccumulation of metals in invertebrates are limited by the same factors that were identified in studies on fishes. Of special note are the rather inconclusive results obtained in studies of arsenic accumulation in the vicinity of a major point source of arsenic in Commencement Bay.

Shrimp, clams, and mussels have been shown to accumulate PCBs in areas of PCB contamination. The degree of PCB bioaccumulation is generally related to the degree of sediment contamination.

Only one study was reviewed that examined pathological conditions in invertebrate organisms. Although the results are somewhat inconclusive due to small sample sizes, there was an indication of increased prevalences of lesions in crabs and shrimp from industrialized areas.

Plankton

Studies of phytoplankton ecology have been conducted near sewage discharges, pulp and paper mill discharges and dredge

spoil disposal sites. The most comprehensive studies were oriented toward effects of the West Point sewage discharge on primary production. Overall, the only indication of effects on phytoplankton at West Point are associated with the possibility of stimulation of primary production during periods of nutrient depletion.

Studies of meroplankton (e.g., ichthyoplankton) have been extremely limited and cause-and-effect pollution-related studies of zooplankton have apparently not been conducted in Puget Sound.

Because of the naturally high levels of spatial and temporal variability of plankton assemblages, studies sufficient to define cause-and-effect relationships must generally be rather intensive. Large numbers of samples collected at relatively short time intervals are generally necessary to define pollutant effects. Because of study design limitations and because of the low probability of pollutant or nutrient impacts in the main basins of Puget Sound, cause-and-effect relationships for plankton have not been established.

Bioaccumulation studies of plankton have concentrated on uptake of PCBs in zooplankton. Tissue levels of PCBs have been shown to be dependent upon PCB concentrations in the water and lipid content of the organisms. Studies of metal accumulation in Puget Sound zooplankton are largely inconclusive.

Toxicity tests using plankton have concentrated on Pacific oyster larvae. Limited studies have also been conducted on the toxic effects of PCBs on phytoplankton and zooplankton. The oyster larvae bioassay has been used extensively in testing a variety of pollutants using mortality and abnormal development as toxic responses. The bioassays have been used to test larval responses to dredge spoils; pulp mill, smelter, and oil refinery effluents; and dinoflagellate blooms. In general, oyster larvae were more sensitive to toxicants than other Puget Sound biota. Thus, the bioassay provides an important mechanism for establishing safe effluent levels for most Puget Sound organisms.

Conclusions

Numerous studies have been conducted in the Puget Sound region that have sought to establish relationships between pollutants and effects on biota or beneficial uses. The presumed causes of biological effects (i.e., pollutant sources) are divided into four main categories in Table 7-3: sewage effluents, pulp and paper mill effluents, dredge spoils, and diverse industrial sources. It should be noted that limited studies have also been conducted near specific industrial sources (e.g., ASARCO smelter), but are not included in the summary table. Important biological effects include

Table 7-3. Occurrence of Studies Examining Relationships Between Pollutant Loading and Biological Effects in Puget Sound

Biological Effects	Pollutant Sources			
	Sewage Effluents	Pulp and Paper Mill Effluents	Diverse Industrial Sources	Dredge Spoils
Fish Abundance	X	X	X	X(L)
Fish Pathology	X		X	
Fish Toxicity	X	X	X(L)	X(L)
Fish Behavior				
Fish Reproduction			X(P)	
Fish Bioaccumulation	X		X	X
Benthos Abundance	X	X	X	X
Benthos Pathology			X(L)	
Benthos Toxicity			X	X
Benthos Behavior				
Benthos Reproduction			X(P)	
Benthos Bioaccumulation	X[a]		X	X
Plankton Abundance (production)	X	X(L)		X(L)
Plankton Toxicity	X	X	X	X
Plankton Bioaccumulation	X(L)		X(L)	X(L)

(X) Data available
(L) Limited information.
(P) Planned or ongoing studies.
[a] Intertidal studies only.

modifications in abundance (or community structure), pathology, toxicity, behavior, reproduction, and bioaccumulation.

For the Puget Sound region, the most intensively studied biological effects include organism abundances, toxicity, and bioaccumulation. Fishes have received the greatest study effort; however, considerable work has also been conducted on assessment of toxicity using benthos and plankton. There is little or no information concerning potential biological effects on behavior and reproduction.

The reviewed studies have produced several kinds of information that characterize biological effects, including identification of effects (or absence thereof) on indigenous biota; identification of tissue contamination and abnormal pathological conditions in organisms inhabiting industrialized areas; and identification of probable relationships between contaminated sediments and bioaccumulation, disease, and mortality of Puget Sound organisms.

Although effects on biota (e.g., fin erosion, bioaccumulation) have been implicated in field studies, information on quantitative cause-and-effect relationships is lacking in many areas. For example, apparent effects of the West Point sewage discharge have been detected in local infaunal communities. However, the available information is not adequate to characterize the cause(s) of the observed effects or to establish a quantitative cause-and-effect relationship. Information required for such determinations would include measurements of solids deposition rates or sediment contaminant concentrations at the same sites used for infaunal benthos sampling. With those kinds of data, changes in biological response variables (e.g., abundance of species A) could be quantitatively related to causative agents.

Studies of bioaccumulation have demonstrated that various contaminants (e.g., PCBs, CBDs, and several metals) occur in elevated concentrations in Puget Sound biota. However, information on uptake routes, intertrophic transfer, and depuration rates is generally lacking. Moreover, quantitative relationships between sediment or water concentrations and organism tissue levels also are not available.

Overall, past studies in the Puget Sound region have served to identify the nature and location of biological effects. Although some cause-and-effect relationships have been established or are suggested by available data, additional studies will be required for the determination of quantitative relationships that are useful for predictive purposes.

Chapter 8

MONITORING PROGRAMS

Introduction

Monitoring programs are established to detect over a period of time changes in environmental conditions or other effects occurring after the onset of certain activities. This chapter describes and evaluates the extent and nature of existing monitoring programs. These programs are evaluated with regard to location, timing, parameters monitored, species and habitats involved, toxicity test and dose-response information, consideration of synergistic effects, and the compatibility of the programs and their data.

Existing Monitoring Programs

Monitoring programs conducted on Puget Sound have changed over the years. When the region began to industrialize, little thought was given to water quality. With development of the pulp mill industry and decline of the oyster population around 1925, water pollution became a recognized problem (Chasan 1981). Since then, regulatory requirements have increased, more precise analytical techniques have been developed, a greater knowledge of toxicity levels has been established, and a greater awareness of ecosystem interactions has developed. As a result, monitoring programs have become more complex and refined over the years.

Monitoring programs generally focus on state water quality standards or on effluent limitations stated in federal water quality criteria. In the majority of cases, available monitoring technology is more sophisticated than that actually used. Time and cost factors often prohibit monitoring of many substances and, in addition, levels of toxicity for many pollutants have still not been determined. For at least these reasons, routine monitoring for substances such as hydrocarbons or pesticides has not been accomplished. Likewise, impacts on the ecosystem and biota are not generally monitored, although it seems desirable to do so.

Monitoring programs may examine either the discharged effluent or the receiving waters. WDOE, Metro, and USGS maintain ongoing programs to monitor Puget Sound waters. Other agencies and groups, including the University of Washington, NOAA, EPA, and the COE, occasionally monitor various areas of the Sound, but they usually do not maintain routine monitoring stations.

However, these agency monitorings do provide short-term discrete bodies of data, and a number of such studies are available in the EPA STORET data system as well as other data bases.

Department of Ecology (WDOE) Programs

NPDES Monitoring and Analysis. NPDES permits are primarily focused on effluent, not receiving waters. Discharge permits under the NPDES program are issued on a case-by-case basis by WDOE. Monitoring is nearly always required as a condition of the permit, except for very small dischargers which typically must maintain only a flow record. Permit conditions normally include: parameters to be monitored, data collection and analysis techniques, monitoring frequency, and reporting schedules. The reports generated from monitoring are called discharge monitoring reports (DMRs), and are filed at the appropriate regional WDOE office semiannually or more frequently, depending on size and type of discharge (Wright pers. comm.). Monitoring is conducted by the permitted discharger; DMRs seldom contain data or information not required by the permit.

In addition to the DMRs, two WDOE programs provide more extensive but less frequent information. A Class I (operation and maintenance) or a Class II (sampling and analysis) inspection is typically carried out by WDOE annually for all major dischargers, although Class II inspections for smaller plants may occur only every 3-4 years. The parameters included in the analysis vary for each Class II inspection, but contain those listed in the discharger's NPDES permit and often a few additional ones, primarily for laboratory checks. Organic priority pollutant analyses are rarely performed. Dischargers to receive Class II inspections are listed in the State/EPA Agreement. This list changes annually; therefore, consecutive, annual Class II reports may not exist for a particular discharger.

Additional inspection analyses may be required for NPDES permit renewal if the discharge is significant or has changed from the previously permitted discharge. Monitoring of conventional, extended conventional, priority pollutants, or additional parameters such as salts may then be required. This monitoring is conducted only once, and is performed by the discharger.

All three NPDES-related monitoring efforts are directed toward monitoring water quality of the effluent before it enters Puget Sound. Little, if any, ambient water monitoring is conducted in conjunction with this program.

301(h) Waiver Application. Several municipal wastewater treatment plants have applied for waivers from secondary treatment, as allowed by Section 301(h) of the CWA. The application must contain an analysis of the effluent that includes conventional, extended conventional, and priority pollutants. The analysis generally represents a single grab or composite sample,

and does not analyze levels in the receiving water. The applications provide some data on effluent composition, but do not provide monitoring data in the strict sense.

River Monitoring. The WDOE surface water quality monitoring stations occur near the mouths of major rivers as well as upstream. These stations have been used for several years to monitor temperature, dissolved oxygen, pH and conductivity, nitrates, phosphates, fecal coliform, turbidity, color, and suspended solids. A few stations also are used to monitor COD; total and dissolved cadmium, chromium, copper, lead, mercury, zinc; and hardness. Limited analyses for pesticides have also been made. Some stations coincide with USGS gaging station locations, and are also sampled by the USGS, as discussed below. Monthly and annual summaries are stored in computer files by WDOE.

Marine Water Monitoring. The WDOE surface water quality monitoring program includes 44 mid-channel stations located in all major areas of Puget Sound and the Straits. Grab samples are collected monthly from April through October. During poor weather months (winter) when runoff and particulate loading are greatest, sampling is not attempted because WDOE uses small planes to transport field personnel (Haines pers. comm.). Marine water is normally analyzed for conventional and extended conventional pollutants including: dissolved oxygen, temperature, water clarity (Secchi disk), fecal coliform bacteria, turbidity, salinity, conductivity, pH, nitrates, and phosphates. At some stations sulfite waste liquor, chlorophyll a, and/or arsenic are also monitored.

Several years of data have been collected and are stored in the WDOE computer as well as in the EPA STORET system. Once a year, as a federal requirement under the Basic Water Monitoring Program (BWMP), WDOE samples the tissues of mussels for metals and some organic pollutants. This involves primarily intertidal mussels. The program has been in operation for several years (Determan pers. comm.).

Intensive Surveys. WDOE conducts a number of intensive surveys directed toward assessing problem areas. The studies are generally short term and site specific, and address such problems as assessing effects of an outfall, determining wasteload allocations for a stream segment, etc. The Ecological Baseline and Monitoring (ECOBAM) program, the longest intensive survey, lasted approximately 7 years and terminated in 1981. This study of Everett Harbor evaluated water quality changes in the harbor as a result of the upgrading of pulp and paper industry discharges. WDOE also monitored biota by use of live box fish bioassays and settling plates (primarily to determine diversity and biomass) (Bernhardt pers. comm.; Determan pers. comm.). Because of their specificity and generally short duration, these surveys should not be considered an integral part of a regional monitoring network.

USGS River Monitoring Program

USGS maintains on larger rivers continuous flow gaging stations which often coincide with WDOE monitoring stations. Where the two stations coincide, USGS obtains the samples. Parameters include those taken by WDOE stations, but often include additional parameters such as phytoplankton and fecal streptococcus bacteria. Sampling at USGS/WDOE stations is generally performed 6 times per year. The flow record often covers a number of years but may not be continuous. Data are published annually by water year and stored on computer.

Metro Monitoring Studies

Seahurst Baseline Study. Metro is conducting a baseline study near the proposed Seahurst outfall; the phase I annual report is due for completion later in 1983. The study includes investigation of the water column, intertidal and subtidal habitats, and microbiology/virology.

The water column study investigates temperature, salinity, oxygen, nutrients (nitrogen, phosphorus, and silica), chlorophyll, particulate matter, zooplankton, phytoplankton, and phytoplankton production. The intertidal study characterizes the infauna, epifauna, microflora, and macroflora. Sediment samples are analyzed for metals, toxic organic compounds, petroleum hydrocarbons, and nutrients. Organisms collected with the sediments are also being identified. Bacterial and viral levels in water, sediment, and shellfish are documented. The fisheries study includes collections and health determinations of existing pelagic and demersal fish. The investigative programs are designed to collect at least 2 years of data, followed by a period of analyzing and synthesizing data, and are concentrating on the Seahurst area, including stations and transects in both East and Colvos Passages. Although not a monitoring program, as defined in Chapter 2, this investigation will provide baseline data useful to any subsequent monitoring effort in the area.

Toxicant Pretreatment Planning Study (TPPS). This 3-year program terminated in July 1983, and provides information for Metro regarding industrial pretreatment and facility planning. Its objectives are to determine what toxic substances enter the Metro collection system and local receiving waters of Puget Sound and Lake Washington; what effects these toxicants are having on the environment and treatment plant operations; where these toxicants come from; and how these materials can be controlled at their sources and through the treatment plants.

Collection system monitoring for metals and organic pollutants includes specific industries; general industrial, commercial and residential areas; plus all process streams at both Renton and West Point treatment plants. Nonpoint sources such as urban runoff and household wastes are also addressed.

Environmental sampling includes water, suspended particulates, and sediments in both Lake Washington and Puget Sound, and from riverine sources. Extensive surveys of benthic community structure are being made near West Point, the Denny Way CSO, and near a storm drain in Lake Washington to identify any correlation between observed changes in benthic community structure and concentrations of toxicants in sediments.

Combined Sewer Overflow Monitoring Program. Several Metro CSOs are automatically monitored, primarily for flow discharge. The flow data are stored in Metro computer files. CSOs currently are being analyzed for a large number of contaminants as part of the Metro TPPS program, and this information could be used in conjunction with flow data to obtain loading and contaminant estimates.

Marine Monitoring Program. Metro's ambient water monitoring program centers around the municipal outfalls and adjacent beaches. Sampling is performed at various depths, and varies from biweekly to quarterly. Parameters typically include dissolved oxygen, suspended solids, and bacteria (total and fecal coliform and fecal streptococcus). Sampling stations are located in concentric rings around the outfall to a distance of about one nautical mile (Tomlinson pers. comm.).

Occasional analyses, primarily for metals, have also been made of water, sediment, and biota in the area near the outfall, but this is not routinely done. Influent and effluent of the plants are monitored on a daily basis for the NPDES program and as part of normal operational procedure. Parameters include a number of conventional pollutants, residual chlorine, and a few others. Metal data are also taken, although most priority pollutants are not included.

Industrial Waste Discharge Monitoring Program. Metro monitors effluent from industries that have a permit to discharge to the Metro collection system. Although these industries do not directly discharge to the study area, a portion of their effluent could directly discharge to marine waters during a CSO event.

Other Monitoring Efforts

Puget Sound Air Pollution Control Agency Air Quality Monitoring. The Puget Sound Air Pollution Control Agency (PSAPCA) has established several air quality stations in Pierce, King, Snohomish, and Kitsap Counties. Parameters potentially impacting Puget Sound through wetfall and dryfall and monitored by PSAPCA include suspended particulates, nitrogen oxides, hydrocarbons, and lead (PSAPCA 1980). Organic pollutants are not monitored. Measurements of concentration in the atmosphere are taken several times a month and summarized in an annual report. Two other air pollution agencies monitor air quality in

other counties adjacent to Puget Sound, but their programs are not as extensive as PSAPCA's.

EPA. EPA does not conduct any routine monitoring, but it occasionally conducts short-term investigations in problem areas (Bogue pers. comm.). A recent Everett Harbor investigation, conducted in conjunction with WDOE, for example, analyzed sediments for priority pollutants and investigated abnormalities in fish. Other areas which have been studied include Commencement Bay and the Duwamish Waterway.

DSHS. DSHS is responsible for monitoring safety of shellfish from commercial clam, mussel, and oyster beds. They do not maintain a routine monitoring of water or in situ shellfish, and do not ordinarily monitor sport shellfish areas. Analyses consist primarily of fecal coliform bacteria in tissues. Shellfish tissue is examined weekly at processing plants. Intensive field surveys lasting 4-10 days are conducted on fecal coliform levels in the water column and sediment in various areas, but there is no established monitoring pattern for the beds themselves.

NOAA. The MESA program was established to develop an understanding of the environmental impacts of human activities on the Puget Sound ecosystem. Over 20 research projects have been conducted under the MESA program, several of which include some form of investigative or monitoring effort. Most of the data that are useful from a monitoring perspective are obtained during sampling of fish and sediments for pollutants. Effort also has been spent on examining ecosystem processes and documenting occurrence of pathological abnormalities in fish. Little information has been compiled to link mass loading to levels in the environment or in the biota, and data are not available to link the occurrence of pollutants in the environment with observed pathological characteristics of the biota. A 2-year effort has recently been started to synthesize these data (Long pers. comm.).

Applicability of Existing Data and Monitoring Methodology to Evaluating and Predicting Cumulative Impacts

Development of a management model ideally requires spatial and temporal knowledge of physical, chemical and biological processes and components in the study area. Knowledge of water, sediment, biota, and habitats is important, as is information on pollutant characteristics, toxicity levels, dose-response data, and synergistic effects.

Several monitoring programs, as well as individual studies involving water, sediment or biota, are ongoing or have been carried out in Puget Sound. Most were designed for use in a

particular area or situation, without thought to their compatibility with previous or ongoing studies by others. While this has allowed each investigator to choose methodologies which best fit his study needs, it has resulted in a wide diversity of sampling and analysis techniques, units of measurement, and types of error. The synthesis of data from these diverse sources is often difficult and, at worst, even inaccurate, because comparisons may be made using data which, due to differences in sampling, are not comparable.

Most monitoring programs have concentrated on one environmental compartment, usually the water column. This may give the misleading impression that a pollutant is absent or in low concentrations, when in fact the concentrations in sediment or biota are quite high. In addition, even water column analyses often do not distinguish between pollutant concentrations in the dissolved state and those associated with suspended matter. In many cases, the chemical species and state is important to toxicity and biological uptake, but it is not identified during the monitoring effort. Also, primarily due to cost considerations, parameters monitored do not normally include such things as polycyclic or monocyclic hydrocarbons, PCBs, or other organic compounds, yet these are often the compounds having the greatest toxicity and potential for bioaccumulation, and in some cases are most clearly associated with adverse effects on organisms and beneficial uses.

In conclusion, these common limitations to existing monitoring programs make it difficult to use these data to evaluate environmental conditions and predict impacts of water quality management decisions. In contrast, private studies often tend to provide more in-depth data, but only for localized areas and over short durations, which makes trend determinations difficult. However, because of their greater detail, short-term studies may ultimately provide data of greater value than those provided by routine water column monitoring. Value of these studies would be enhanced if collection and analysis procedures can be standardized to allow comparison of study results.

Chapter 9

SYNTHESIS OF FINDINGS

The purpose of this chapter is two-fold. First, we discuss how available information on pollutants; mass loading of pollutants (Chapter 4), distribution in the environment (Chapters 5, 6, and 7), and effects on the biota (Chapter 7); can be used to predict impacts of pollutants on beneficial uses and resources of Puget Sound. This discussion focuses on the ability of resource managers to predict impacts resulting from regulatory decisions, based on knowledge of how pollutant loading is linked to adverse impacts on beneficial uses (see Chapter 3, Figure 3-1, and Table 3-1). Second, in evaluating the usefulness of the existing data base, we begin to identify areas that have been improperly or inadequately documented.

To simplify the discussion of the usefulness of the existing data base to decision making, the discussion is separated into two sections. The first section describes management's ability, using existing information, to trace a pollutant from the source to its eventual distribution in Puget Sound. The second section of the discussion describes ability, using existing information, to trace pollutants in the environment to their eventual distribution in the biota, and how they affect species.

Pollutants in Puget Sound

Linkages between the inputs of pollutants and their eventual distributions in the environment can only be generally outlined by the existing data base. Water quality managers are therefore faced with isolated pieces of information and often must rely on educated guesses in predicting impacts resulting from their management decisions.

Mass Loading Data

Mass loading data are generally incomplete or inadequate for their needed uses. Mass loadings of conventional pollutants (e.g., BOD) from major point sources and major rivers are generally well documented and usable by resource managers, but many conventional pollutants are of relatively little concern except in localized areas with poor flushing (e.g., Budd Inlet).

Few data are available on the mass loading of heavy metals to Puget Sound. Most of these data are provided by Metro and by

industrial dischargers in Commencement Bay. Some data on riverine input and atmospheric deposition of heavy metals are also available, but these are limited to only a few metals at a few locations. Absence of data on riverine input of heavy metals during the winter is another limitation to these data. Additional data for CSOs and storm drain runoff in the Metro service area will soon be available with completion of the Toxicant Pretreatment Planning Study (TPPS) by Metro. Heavy metal mass loading, even for the Metro service area, will be incomplete until data are also available from industrial dischargers.

Another, and more severe problem with existing mass loading data, is the widespread absence of data on the mass loading of the organic priority pollutants. Metro and industrial dischargers in Commencement Bay have provided some information, but analytical procedures in certain cases result in inaccurate data. For example, some analyses of effluent composition are made prior to chlorination. Many chlorinated compounds, including some priority pollutants, may be formed during the chlorination process; therefore, mass loading of these compounds could be underestimated if measurable quantities of these compounds are formed. In other cases the analytical methodology may not accurately assess concentrations. For example, "oil and grease" measurements do not normally accurately reflect hydrocarbon content because the low boiling fractions are typically lost during analysis (Pizzo et al. 1976). In still other cases, a toxic material may escape notice simply because it is not considered a priority pollutant or is not a parameter covered by water quality standards. The industrial pretreatment program is attempting to identify compounds of this sort. A closer look at regional industries not discharging to municipal systems might disclose toxic materials which have escaped the monitoring process.

A third major problem that hinders the water quality manager's ability to use the existing data base is lack of information on mass loading from nonpoint sources. This problem is of particular concern in shellfish growing areas and at dredge spoil disposal sites.

Transport, Fate and Distribution in the Physical Habitat

The resource manager can predict the movement of pollutants between water masses on a very broad scale, and it is possible to adequately model nearfield discharge plumes and zones of dilution, but managers typically do not have the information needed to model transport of pollutants between these two extremes. Generally a major portion of the pollutant load is adsorbed to fine particulate matter and is transported to deposition environments within the regional receiving water but outside the nearfield zone. Furthermore, nearfield models rarely address the role of flocculation and sedimentation

rates in depositing pollutants in the nearfield. Ambient currents play a major role in the deposition of particulate matter. Areas with strong currents typically have coarse-grained sediments. Fine particulate matter is unlikely to permanently settle in these areas, and may be transported for some distance before it can settle out. Existing modeling efforts rarely address this sedimentation problem. Studies have not been conducted that concurrently examine pollutant loading, dispersal paths and processes, and deposition in the sediments. A few monitoring efforts have been made that concurrently sample outfall suspended solids and sediments in the nearfield, but these provide little meaningful data in the absence of dispersal information.

Chemical compounds having similar structures often display similar properties. It is possible, therefore, to generally predict the physical or chemical fate of most pollutants based on known properties associated with the general chemical structure. The ability to make predictions is hampered, however, for several reasons. First, speciation of pollutants affects their toxicity and fate, but existing data frequently do not identify the form or isomer of a compound. Similarly, pollutants in the dissolved state have quite different properties relative to those in the adsorbed state. The existing data frequently do not identify whether the pollutant is in a dissolved or adsorbed state. Second, local conditions play a significant role in determining the fate of pollutants. Much of the existing fate information is based on studies in freshwater systems. Marine processes can be expected to differ. Although it may be possible to identify the various physical and chemical processes that alter the form and distribution of pollutants, it is usually not possible to determine with existing data which processes are most important locally. Third, a number of compounds produce degradation products that are as toxic or even more toxic than the parent compound. In the case of many organic pollutants, the degradation products remain unknown or have not been sought in the existing data. Finally, phenomena such as synergistic effects and chemical interaction of pollutants are rarely understood or reported.

Effects of Pollutants on Biota

Sindermann (1979) has pointed out that when scientists are asked to "state positively that the disease condition seen in natural populations is caused by specific environmental contaminants," the scientist cannot do so; however, the weight of evidence "leads to the conclusion that associations do exist between pollutants and disease." This dilemma for the resource manager is no different in Puget Sound. We do know, however, from the evidence obtained in Puget Sound that:

- The occurrence of fish disease and the concentration of organic compounds in fish and sediments are higher in urbanized embayments than in other areas.
- Municipal and industrial effluent are toxic in specific cases to a wide array of organisms.
- In a few tests, sediments from certain areas are toxic to certain organisms.
- Skin tumors of demersal fish may be accompanied by differential growth and mortality.

The key data that are missing in each of the above observations is knowledge of the specific contaminant that results in the effect. As described below, the existing data do not allow the resource manager to determine that regulatory decisions will alter the adverse impacts of specific pollutants on biota.

Heavy Metals

There have been no definitive studies that demonstrate the bioaccumulation of heavy metals in fish tissues above "normal" or "background" concentrations. None of the studies to date has included sufficient replicates to allow statistical analysis of the data. The existing data are from a variety of fish species, but nothing is known about species-specific susceptibility to the bioaccumulation of metals. Many of the existing studies are of no value because samples were not collected from an appropriate control area (either no control samples were taken, or the unpolluted status of the control area was not verified). No efforts have been made to date to calibrate the procedures and results of the various laboratories that have conducted the analyses. Finally, existing data are plagued by inconsistency in the unit measurements reported (e.g., dry vs. wet weight).

Apart from mercury, a literature survey indicates that bioaccumulation of heavy metals by fish in Puget Sound is not likely. Arsenic, lead, and copper could be of localized concern in Puget Sound, but the existing studies have not concurrently sampled levels of these metals in fish, sediments, the diet, and the water column. At the moment, the data indicate that heavy metal contamination of sediments may be correlated with the occurrence of pathological conditions, but this is not evidence of a cause-and-effect relationship.

PCBs

Available data on the concentrations of PCBs (and similarly for most other organic contaminants) in fishes of Puget Sound present many of the same problems found in the data on concentrations of metals in fishes (e.g., lack of adequate replication, differences in fish species analyzed, lack of appropriate controls, and variations in both analytical procedures and in the units reported). Nevertheless, these data are

more suggestive of significant bioaccumulation because the differences in the concentrations of these compounds between fish in known polluted areas and those in background or control areas are much larger than are the usual differences in metals concentrations between two such areas. Whereas metals concentrations often only differ two- or three-fold between fish in polluted urban areas and those in presumed control areas, the concentrations of PCBs in fish from two such areas often differ by one or more orders of magnitude. The available evidence suggests that accumulation of PCBs is most pronounced in demersal fishes (e.g., English sole, rock sole, sculpins) inhabiting urban estuaries (e.g., Commencement Bay, Elliott Bay, Duwamish River) known to have sediments contaminated with comparably high concentrations of these compounds.

As in the case of some heavy metals, it is known that PCBs are toxic to many organisms at low concentrations. Data from the literature indicate that PCBs are taken up from sediments and from the water column, and that PCBs induce some of the pathological conditions observed in fish in urbanized embayments of Puget Sound. These latter observations, although obtained under laboratory conditions, are evidence that PCBs may be causing some of the observed pathologies of fishes. This does not, however, constitute evidence that PCBs are the only causal agent for fish abnormalities in Puget Sound.

Other Organic Compounds

A number of organic compounds known to be highly toxic to marine organisms have been found in Puget Sound, e.g., DDT and derivatives, other pesticides, chlorinated butadienes, polychlorinated phenols, and higher molecular weight polyaromatic hydrocarbons. In all cases, evidence to show that these are causal agents for fish abnormalities in Puget Sound has not been obtained, for some of the same reasons that such evidence has not been obtained for heavy metals and PCBs.

Summary

With a few exceptions, available data do not clearly link specific pollutants to adverse impacts on beneficial uses; nevertheless, the weight of the circumstantial evidence indicates a positive association between wastewater discharge and changes in or adverse impacts on beneficial uses. The water quality manager is faced with the knowledge that regulatory decisions currently cannot be focused on the causal agents of observed symptoms of water pollution, and there is, therefore, no assurance that a decision will be the correct one, i.e., one that will remedy or abate the adverse impact. In the face of this dilemma, the water quality manager may well ask how existing data can be used until such time that appropriate data are made available.

Two sets of observations can be of use to water quality managers at the present time. First, in the absence of

documented cause-and-effect relationships between specific pollutants and pathological abnormalities observed in fish populations, it may be valid to look for pollution characteristics common to those localities. In reviewing contaminants in the environments of diseased fish in areas such as Elliott Bay, Commencement Bay, coastal Southern California, and Chesapeake Bay, the most obvious similarity is the presence in the sediments of a number of chlorinated hydrocarbons, especially PCBs, pesticides, and compounds typically associated with wastewater chlorination. Among these pollutants, PCBs have usually been detected in fish tissues, but the concentrations vary widely and no meaningful correlation between levels in tissues and incidence of disease can be obtained.

Second, although documented cause-effect relationships may not be currently available, there is a large body of information suggesting a positive correlation between certain pollution conditions and observed effects on biota or beneficial uses. In some cases, these correlations can be useful indicators for choosing appropriate regulatory decisions, e.g., whether to issue a new source permit or alter wastewater treatment practices in a local area if other options are available.

At the present time, the quantities or mass loading of pollutants discharged to various areas of Puget Sound are generally uninterpretable for possible cause-and-effect purposes, with the possible exception of Elliott and Commencement Bays. Even in these two areas, it seems likely that sufficient data are not available. For example, loading from CSOs is not presently incorporated into mass loading calculations. CSOs represent short-term, seasonal, but potentially major, loading events. Even if data were available, too little is known about the transport and fate mechanisms to determine whether CSOs can be dealt with on an average daily basis or as seasonal events. Furthermore, some industries on these two bays may discharge low volumes of effluent that represent significant loading sources that current monitoring efforts overlook, because toxic constituents are not on the EPA priority pollutant list.

Existing circulation modeling efforts are generally useful to water quality managers to predict dilution rates and dilution zones of the outfall plume. Some models may help estimate the flushing rate for a localized water body, but all of these models describe dilution of the wastewater and, therefore, describe the likely transport of dissolved pollutants and pollutants adsorbed to suspended particulates that remain in the water column during the dilution period.

Conclusion

Water quality managers have the regulatory tools to respond and prevent and abate pollution once there is sufficient evidence to show reasonable cause that a discharge or polluting activity has an adverse effect on beneficial uses or resources. Although a comprehensive water quality management structure is operating, it is not fully integrated and coordinated with respect to the acquisition and use of technical data and information.

With the exception of effluent analyses done as part of the 301(h) waiver applications for municipal discharges, and as NPDES permit compliance monitoring on behalf of a few selected industrial discharges, there are few data to describe sources and mass loadings of priority pollutants. Although the EPA priority pollutant list is a reasonable starting point for identifying pollutants requiring special consideration in Puget Sound, the list should be used in conjunction with other factors. Many of the compounds on the list have not been found in the Puget Sound ecosystem, while a few other compounds known to be toxic, but not on the list, have been found.

Knowledge about the dispersion and fate of pollutants is based primarily on theoretical considerations, simplifying models, and limited empirical data identifying where certain toxicants have accumulated in the environment. The build-up of potentially toxic substances in bottom sediments is documented, particularly in the Central Basin. These data indicate highly localized distributions of contaminants in the sediments.

The acutely toxic characteristics of priority pollutants are well documented (otherwise they would not have been designated as an EPA priority pollutant). Pathogenic conditions observed in some demersal fish, especially English sole and starry flounder, are inferentially associated with bottom sediments containing abnormally high concentrations of toxicants. Generally, there are few data that link indirect effects on biota with specific pollutants, much less with sources of pollutants.

Water quality monitoring in Puget Sound is done primarily by WDOE, NPDES permittees, USGS, and DSHS. In some cases, the objectives of monitoring are not given or are poorly defined. Although conventional pollutants are often included in monitoring, priority pollutants are usually not included, and consistency is lacking in the coordination of sampling and data treatment to permit maximum uses of all data.

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LIST OF PREPARERS

Name & Firm		Field of Expertise	Responsibility
Dr. C. Hazel	JSA	Water quality, biology	Program manager; contribution to Chapter 1.
Dr. H. Van Veldhuizen	JSA	Marine biology	Project manager; Chapters 1, 2, 3, 9; contributions to Chapters 4, 6, 7 & 8.
Ms. A. Godbey	JSA	Water quality, engineering	Chapter 4; contribution to Chapter 8.
Mr. G. Ruggerone	JSA	Fisheries biology	Contribution to Chapter 4.
Ms. J. Cabreza	JSA	Water quality, biology	Chapter 6; contribution to Chapters 8 & 9.
Mr. R. Denman	JSA	Stream hydrology	Contribution to Chapter 4.
Dr. T. Ginn	TTI	Marine biology	Chapter 7; contribution to Chapter 9.
Dr. L. McCrone	TTI	Fisheries biology	Contribution to Chapter 7.
Mr. G. Bigham	TTI	Oceanographic modeling	Chapter 5.
Ms. L. Little	TTI	Oceanographic modeling	Contribution to Chapter 5.
Mr. J. Pagenkopf	TTI	Oceanographic modeling	Contribution to Chapter 5.

JSA - Jones & Stokes Associates, Inc.

TTI - Tetra Tech, Inc.

APPENDIX A

Priority Pollutants Identified by EPA

(1) *acenaphthene
(2) *acrolein
(3) *acrylonitrile
(4) *benzene
(5) *benzidine
(6) *carbon tetrachloride (tetrachloromethane)

*chlorinated benzenes (other than dichlorobenzenes)
(7) chlorobenzene
(8) 1,2,4-trichlorobenzene
(9) hexachlorobenzene

*chlorinated ethanes (including 1,2-dichloroethane, 1,1,1-trichloroethane, and hexachloroethane)
(10) 1,2-dichloroethane
(11) 1,1,1-trichloroethane
(12) hexachloroethane
(13) 1,1-dichloroethane
(14) 1,1,2-trichloroethane
(15) 1,1,2,2-tetrachloroethane
(16) chloroethane

*chloroalkyl ethers (chloromethyl, chloroethyl, and mixed ethers)
***(17) bis(chloromethyl) ether
(18) bis(2-chloroethyl) ether
(19) 2-chloroethyl vinyl ether (mixed)

*chlorinated naphthalenes
(20) 2-chloronaphthalene

*chlorinated phenols (other than those listed elsewhere; includes trichlorophenols and chlorinated cresols)
(21) 2,4,6-trichlorophenol
(22) para-chloro meta-cresol
(23) *chloroform (trichloromethane)
(24) *2-chlorophenol

*dichlorobenzenes
(25) 1,2-dichlorobenzene
(26) 1,3-dichlorobenzene
(27) 1,4-dichlorobenzene

*dichlorobenzidine
(28) 3,3'-dichlorobenzidine

*dichloroethylenes (1,1-dichloroethylene and 1,2-trans-dichloroethylene)
(29) 1,1-dichloroethylene
(30) 1,2-trans-dichloroethylene
(31) *2,4-dichlorophenol

*dichloropropane and dichloropropene
(32) 1,2-dichloropropane
(33) 1,2-dichloropropylene (1,2-dichloropropene)
(34) *2,4-dimethylphenol

*dinitrotoluene
(35) 2,4-dinitrotoluene
(36) 2,6-dinitrotoluene
(37) *1,2-diphenylhydrazine
(38) *ethylbenzene
(39) *fluoranthene

*haloethers (other than those listed elsewhere)
(40) 4-chlorophenyl phenyl ether
(41) 4-bromophenyl phenyl ether
(42) bis(2-chloroisopropyl) ether
(43) bis(2-chloroethoxy) methane

*halomethanes (other than those listed elsewhere)
(44) methylene chloride (dichloromethane)
(45) methyl chloride (chloromethane)
(46) methyl bromide (bromomethane)
(47) bromoform (tribromomethane)
(48) dichlorobromomethane
***(49) trichlorofluoromethane
***(50) dichlorodifluoromethane
(51) chlorodibromomethane
(52) *hexachlorobutadiene
(53) *hexachlorocyclopentadiene
(54) *isophorone
(55) *naphthalene
(56) *nitrobenzene

*nitrophenols (including 2,4-dinitrophenol and dinitrocresol)
(57) 2-nitrophenol
(58) 4-nitrophenol
(59) 2,4-dinitrophenol
(60) 4,6-dinitro-o-cresol

*nitrosamines
(61) N-nitrosodimethylamine
(62) N-nitrosodiphenylamine
(63) N-nitrosodi-n-propylamine
(64) *pentachlorophenol
(65) *phenol

*phthalate esters
(66) bis(2-ethylhexyl) phthalate
(67) butyl benzyl phthalate
(68) di-n-butyl phthalate
(69) di-n-octyl phthalate
(70) diethyl phthalate
(71) dimethyl phthalate

*polynuclear aromatic hydrocarbons
(72) benzo[a]anthracene (1,2-benzanthracene)
(73) benzo[a]pyrene (3,4-benzopyrene)
(74) 3,4-benzofluoranthene
(75) benzo[k]fluoranthene (11,12-benzofluoranthene)
(76) chrysene
(77) acenaphthylene
(78) anthracene
(79) benzo[ghi]perylene (1,12-benzoperylene)
(80) fluorene
(81) phenanthrene
(82) dibenzo[a,h]anthracene (1,2,5,6-dibenzanthracene)
(83) indeno[1,2,3-cd]pyrene
(84) pyrene
(85) *tetrachloroethylene
(86) *toluene
(87) *trichloroethylene
(88) *vinyl chloride (chloroethylene)

*pesticides and metabolites
(89) *aldrin
(90) *dieldrin
(91) *chlordane (technical mixture and metabolites)

*DDT and metabolites
(92) 4,4'-DDT
(93) 4,4'-DDE (p,p'-DDX)
(94) 4,4'-DDD (p,p'-TDE)

*endosulfan and metabolites
(95) a-endosulfan-Alpha
(96) b-endosulfan-Beta
(97) endosulfan sulfate

*endrin and metabolites
(98) endrin
(99) endrin aldehyde

*heptachlor and metabolites
(100) heptachlor
(101) heptachlor epoxide

*hexachlorocyclohexane (all isomers)
(102) a-BHC-Alpha
(103) b-BHC-Beta
(104) r-BHC (lindane)-Gamma
(105) g-BHC-Delta

*polychlorinated biphenyls (PCBs)
(106) PCB-1242 (Aroclor 1242)
(107) PCB-1254 (Aroclor 1254)
(108) PCB-1221 (Aroclor-1221)
(109) PCB-1232 (Aroclor-1232)
(110) PCB-1248 (Aroclor-1248)
(111) PCB-1260 (Aroclor-1260)
(112) PCB-1016 (Aroclor-1016)
(113) *toxaphene
(114) *antimony (total)
(115) *arsenic (total)
(116) *asbestos (fibrous)
(117) *beryllium (total)
(118) *cadmium (total)
(119) *chromium (total)
(120) *copper (total)
(121) *cyanide (total)
(122) *lead (total)
(123) *mercury (total)
(124) *nickel (total)
(125) *selenium (total)
(126) *silver (total)
(127) *thallium (total)
(128) *zinc (total)
(129) **2,3,7,8-tetrachlorodibenzo-p-dioxin

NOTES: *Specific compounds and chemical classes as listed in the consent decree.

**This compound was specifically listed in the consent decree: however, due to its extreme toxicity we are recommending that laboratories not acquire an analytical standard for this compound.

***No longer on priority pollutant list.

Appendix B

NPDES PERMITTED DISCHARGERS TO PUGET SOUND

Map ID number refers to Figure 4-1. Individual dischargers are designated by county and with an individual number. County names used in the ID number are abbreviated in Figure 4-1 as follows:

W = Whatcom
SK = Skagit
SN = Snohomish
K = King
S = San Juan
I = Island
KT - Kitsap
P = Pierce
T = Thurston
C = Clallam
M = Mason
J = Jefferson

NPDES Permitted Dischargers to Puget Sound

Permit No.	Discharger	Receiving Water	Map ID No.
WA-0022900	ARCO	STRAIT OF GEORGIA	WHATCOM 1
WA-0023744	CITY OF BELLINGHAM	BELLINGHAM BAY	WHATCOM 2
WA-0002143	BELLINGHAM COLD STORAGE C	SQUALICUM CK AND BOAT BASIN	WHATCOM 3
WA-0029238	BORNSTEIN SEAFOOD INC	I & J ST. WATERWAY	WHATCOM 4
WA-0002879	BUMBLE BEE SEAFOODS	SQUALICUM BOAT BASIN	WHATCOM 5
WA-0001198	COLUMBIA CEMENT CORP	BELLINGHAM BAY	WHATCOM 6
WA-0029408	DAHL FISH CO	WHATCOM CK WATERWAY	WHATCOM 7
WA-0001091	GEORGIA-PACIFIC CORP	BELLINGHAM BAY	WHATCOM 8
WA-0030392	GEORGIA PACIFIC CORP	WHATCOM WATERWAY	WHATCOM 9
WA-0023787	WA ST. PARK & REC COMMISH	SAMISH BAY	WHATCOM 10
WA-0002984	MOBIL OIL CORP (FERNDALE)	STRAIT OF GEORGIA	WHATCOM 11
WA-0021482	MT. BAKER PLYWOOD	SQUALICUM WATERWAY	WHATCOM 12
WA-0029866	OLIVINE CORP	BELLINGHAM BAY	WHATCOM 13
WA-0002852	R.G. HALEY INTERNAT'L COR	BELLINGHAM BAY	WHATCOM 14
WA-0029815	SEA PAC CO.	BELLINGHAM BAY	WHATCOM 15
WA-0030601	PUGET SOUND POWER & LIGHT	GEORGIA STRAITS	WHATCOM 16
WA-0022641	CITY OF BLAINE	STRAIT OF GEORGIA	WHATCOM 17
WA-0029556	WHATCOM CO. WATER DIST 8	STRAIT OF GEORGIA	WHATCOM 18
WA-0030350	LIQUID CARBONIC CORP	STRAIT OF GEORGIA	WHATCOM 19
WA-0002950	INTALCO ALUMINUM (FERNDL)	STRAIT OF GEORGIA	WHATCOM 20
WA-0020257	CITY OF ANACORTES	GUEMES CHANNEL	SKAGIT 1
WA-0029441	CITY OF ANACORTES	BURROWS BAY	SKAGIT 2
WA-0001406	ALLIED CHEMICAL CORP	PADILLA BAY	SKAGIT 3
WA-0002402	FISHERMAN'S PACKING CORP	GUEMES CHANNEL	SKAGIT 4
WA-0002836	LEONA M. SUNQUIST MAR LAB	GUEMES CHANNEL	SKAGIT 5
WA-0001821	PUBLISHERS FOREST PROD CO	FIDALGO BAY	SKAGIT 6
WA-0000761	SHELL OIL CO	FIDALGO BAY	SKAGIT 7
WA-0002941	TEXACO, INC.	FIDALGO BAY	SKAGIT 8
WA-0003336	WHITNEY FIDALGO SEAFOODS	GUEMES CHANNEL	SKAGIT 9
WA-0002607	ROCK POINT OYSTER CO	SAMISH BAY	SKAGIT 10
WA-0029262	BLAU OYSTER CO	SAMISH BAY	SKAGIT 11
WA-0022446	TOWN OF LA CONNER	SWINOMISH SLOUGH	SKAGIT 12
WA-0003506	MOORE CLARK CO.	SWINOMISH CHANNEL	SKAGIT 13
WA-0024422	SHELTER BAY COMMUNITY INC	SWINOMISH CHANNEL	SKAGIT 14
WA-0030490	SOMETHING FISHY FISH CO.	SWINOMISH CHANNEL	SKAGIT 15
WA-0029432	SKAGIT CO. SEWER DIST. #1	SKAGIT BAY	SKAGIT 16
WA-0025062	SWINOMISH INDIAN TRIBAL	SWINOMISH CHANNEL	SKAGIT 17
WA-0003425	NEW ENGLAND FISH CO.	SWINOMISH CHANNEL	SKAGIT 18
WA-0030031	WHITNEY FIDALGO SEAFOODS	SALMON BAY	SKAGIT 19

NPDES Permitted Dischargers to Puget Sound

Permit No.	Discharger	Receiving Water	Map ID No.
WA-0029025	AIRCO WELDING CO.	DUWAMISH R.	KING 1
WA-0029696	ARCO	DUWAMISH WATERWAY	KING 2
WA-0029017	METRO - ALKI	PUGET SOUND	KING 3
WA-0000744	BETHLEHEM STEEL CORP	ELLIOT BAY (STORM DITCH)	KING 4
WA-0030368	BOEING AEROSPACE COM	DUWAMISH R.	KING 5
WA-0003514	BOEING	DUWAMISH R.	KING 6
WA-0002917	BOEING	DUWAMISH R.	KING 7
WA-0030716	BOEING	DUWAMISH R. VIA STORM SEW	KING 8
WA-0000868	BOEING	DUWAMISH	KING 9
WA-0029874	BOEING	DUWAMISH R.	KING 10
WA-0029173	METRO - CARKEEK	PUGET SOUND	KING 11
WA-0002488	CHAMPION BUILDING PRODUCT	LAKE WASHINGTON SHIP CANAL	KING 12
WA-0001856	COLUMBIA CEMENT	WEST WATERWAY	KING 13
WA-0020958	DES MOINES SEWER DIST	PUGET SOUND	KING 14
WA-0021351	FISHER MILLS	DUWAMISH WATERWAY	KING 15
WA-0022144	GATX TANK STORAGE TERMIN.	DUWAMISH E. WATERWAY	KING 16
WA-0002232	IDEAL BASIC INDUSTRIES	DUWAMISH R.	KING 17
WA-0002259	KAISER CEMENT & GYPSUM	DUWAMISH	KING 18
WA-0022624	LAKEHAVEN SEWER DISTRICT	PUGET SOUND-DUMAS BAY	KING 19
WA-0023451	LAKEHAVEN SEWER DIST	PUGET SOUND-POVERTY BAY	KING 20
WA-0020753	LIQUID AIR, INC.	DUWAMISH R.	KING 21
WA-0000558	LOCKHEED SHIPBUILDING COR	DUWAMISH R. W. WATERWAY	KING 22
WA-0029220	MARALCO ALUM	DUWAMISH R.	KING 23
WA-0029009	MOBIL OIL CORP	ELLIOTT BAY	KING 24
WA-0003395	MOBIL OIL CORP.	L. W. SHIP CANAL	KING 25
WA-0021270	MONSANTO CO.	STR. OF JUAN DE FUCA	KING 26
WA-0003093	MONSANTO IND. CHEM CO.	DUWAMISH R.	KING 27
WA-0029122	N. COAST CHEM CO.	DUWAMISH WATERWAY VIA DITCH	KING 28
WA-0001295	N W BOLT & NUT CO	LK. WASH. SHIP CANAL	KING 29
WA-0002046	N.W. STEEL ROLLING MILLS	LAKE WASH. SHIP CANAL	KING 30
WA-0003433	NORTHWESTERN GLASS CO.	DUWAMISH RIVER	KING 31
WA-0001431	QUEMETCO, INC.	WEST WATERWAY VIA STORM SEWER TRIB	KING 32
WA-0029611	METRO - RICHMOND	PUGET SOUND	KING 33
WA-0022306	SEABOARD LUMBER CO.	DUWAMISH WATERWAY	KING 34
WA-0003280	CITY OF SEATTLE	DUWAMISH RIVER	KING 35
WA-0001597	SEATTLE STEAM CORP	ELLIOT BAY	KING 36
WA-0001503	SEATTLE STEAM CORP	ELLIOTT BAY	KING 37

NPDES Permitted Dischargers to Puget Sound

Permit No.	Discharger	Receiving Water	Map ID No.
WA-0024651	PORT OF SEATTLE IND WST P	PUGET SOUND	KING 38
WA-0022764	S.W. SUB. SEW. D.(MILLER)	PUGET SOUND	KING 39
WA-0022772	S.W. SUB. SEW. D.(SALMON)	PUGET SOUND	KING 40
WA-0003085	SHELL OIL	ELLIOTT BAY	KING 41
WA-0001279	STD. OIL CO. OF CALIF.	EAST DUWAMISH WATERWAY	KING 42
WA-0001791	TEXACO INC.	DUWAMISH WATERWAY	KING 43
WA-0002615	TODD SHIPYARDS CORP	ELLIOTT BAY	KING 44
WA-0022527	VASHON SEWER DISTRICT	PUGET SOUND	KING 45
WA-0029181	METRO - WEST POINT	PUGET SOUND AT WEST POINT	KING 46
WA-0029386	PENN COVE SEWER DISTRICT	PENN COVE	ISLAND 1
WA-0020567	CITY OF OAK HARBOR	OAK HARBOR	ISLAND 2
WA-0020702	TOWN OF LANGLEY	SARATOGA PASSAGE	ISLAND 3
WA-0003468	NAVAL AIR STATION	CRESENT HARBOR	ISLAND 4
WA-0029378	TOWN OF COUPEVILLE	PENN COVE	ISLAND 5
WA-0029190	J.J.THEODORE CO.	GRIFFEN BAY	SAN JUAN 1
WA-0030571	EASTSOUND WATER DIST	PRESIDENT CHANNEL	SAN JUAN 2
WA-0029891	ROSARIO RESORT DEVELOPMNT	CASCADE BAY, EASTSOUND	SAN JUAN 3
WA-0023582	TOWN OF FRIDAY HARBOR	FRIDAY HARBOR	SAN JUAN 4
WA-0029637	U OF WA FRI. HARBOR LAB.	SAN JUAN CHANNEL	SAN JUAN 5
WA-0030589	FISHERMAN BAY SEWER DIST.	SAN JUAN CHANNEL	SAN JUAN 6
WA-0029211	ISLAND FRESH SEAFOODS	OUTER BAY	SAN JUAN 7
WA-0021822	ROCHE HARBOR RESORT	ROCHE HARBOR	SAN JUAN 8
WA-0030431	FRIDAY HARBOR WATER DEPT	FALSE BAY	SAN JUAN 9
WA-0029904	FREE METHODIST CHURCH OF	PORT SUSAN	SNOHOMISH 1
WA-0003239	STANDARD OIL OF CALIFORNI	PUGET SOUND	SNOHOMISH 2
WA-0023396	OLYMPUS TERRACE SEWER DIS	POSSESSION SOUND	SNOHOMISH 3
WA-0024031	CITY OF LYNNWOOD	BROWN BAY PUGET SOUND	SNOHOMISH 4
WA-0023299	CITY OF MUKILTEO	POSSESSION SOUND	SNOHOMISH 5
WA-0020893	LAKE STEVENS SEWER DIST	EBEY SLOUGH	SNOHOMISH 6
WA-0022497	CITY OF MARYSVILLE	EBEY SLOUGH	SNOHOMISH 7
WA-0020826	ALDERWOOD WATER DISTRICT	PUGET SOUND	SNOHOMISH 8
WA-0000621	SCOTT PAPER CO	EVERETT HARBOR	SNOHOMISH 9
WA-0003417	WESTERN GEAR CORP	PORT GARDNER	SNOHOMISH 10
WA-0024490	CITY OF EVERETT	SNOHOMISH RIVER	SNOHOMISH 11
WA-0001775	UNION OIL OF CALIFORNIA	PUGET SOUND	SNOHOMISH 12
WA-0024058	CITY OF EDMONDS	PUGET SOUND	SNOHOMISH 13
WA-0025232	DEFENSE FUEL SUPPORT PT.	POSSESSION SOUND	SNOHOMISH 14
WA-0024805	TULALIP TRIBES OF WASH	POSSESSION SOUND	SNOHOMISH 15
WA-0025097	NOAA FISHERIES RESEARCH F	POSSESSION SOUND	SNOHOMISH 16
WA-0020290	CITY OF STANWOOD	STILLAGUAMISH RIVER	SNOHOMISH 17

NPDES Permitted Dischargers to Puget Sound

Permit No.	Discharger	Receiving Water	Map ID No.
WA-0025241	TULALIP TRIBES	TULALIP BAY	SNOHOMISH 20
WA-0003000	WEYERHAEUSER CO.	STEAMBOAT SLOUGH	SNOHOMISH 18
WA-0003590	WEYERHAEUSER CO.	SNOHOMISH RIVER	SNOHOMISH 19
WA-0023957	TOWN OF GIG HARBOR	PUGET SOUND - GIG HARBOR	PIERCE 1
WA-0002135	MINTERBROOK OYSTER CO.	PUGET SOUND, HENDERSON BAY	PIERCE 2
WA-0038920	WOLLOCHET HARBOR CLUB	WOLLOCHET BAY	PIERCE 3
WA-0037575	KETRON ISLAND ENTERPRISES	PUGET SOUND	PIERCE 4
WA-0037656	TAYLOR BAY BEACH CLUB	TAYLOR BAY/CASE INLET	PIERCE 5
WA-0021946	U.S. PENITENTIARY-MCNEIL	PUGET SOUND	PIERCE 6
WA-0037044	TOWN OF STEILACOOM	PUGET SOUND	PIERCE 7
WA-0001040	BOISE CASCADE	PUGET SOUND CHAMBERS CR.	PIERCE 8
WA-0000582	GLACIER SAND & GRAVEL	PUGET SOUND	PIERCE 9
WA-0037214	TACOMA NORTH END PLT #3	COMMENCEMENT BAY	PIERCE 10
WA-0037087	CITY OF TACOMA PLANT #1	PUYALLUP RIVER	PIERCE 11
WA-0037206	CITY OF TACOMA PLANT #2	PUGET SOUND NARROWS	PIERCE 12
WA-0000647	ASARCO INC.	COMMENCEMENT BAY	PIERCE 13
WA-0022918	ATLAS FOUNDRY & MACHINE C	CITY WATERWAY VIA TAC. STORM SEWER	PIERCE 14
WA-0002321	BUFFELEN WOODWORKING CO.	HYLEBOS WATERWAY, COMMENCEMENT BAY	PIERCE 15
WA-0037958	CASCADE POLE CO.	BLAIR WATERWAY VIA TACOMA STORN SEW	PIERCE 16
WA-0001287	CERTAIN TEED PRODUCTS COR	COMMENCEMENT BAY	PIERCE 17
WA-0001864	CONCRETE TECH CORP	BLAIR WATERWAY	PIERCE 18
WA-0001007	DOMTAR CHEMICAL CO	BLAIR WATERWAY COMMENCEMENT BAY	PIERCE 19
WA-0037851	FICK FOUNDRY CO	CITY WATERWAY	PIERCE 20
WA-0003298	GEORGE SCOFIELD CO	CITY WATERWAY COMMENCEMENT BAY	PIERCE 21
WA-0037265	HOOKER CHEMICAL & PLASTIC	HYLEBOS WATERWAY COMMENCEMENT BAY	PIERCE 22
WA-0020788	HYDRADE FOOD PROD CORP	WHEELER OSGOOD WATERWAY VIA ST.DR.	PIERCE 23
WA-0000931	KAISER ALUMINUM & CHEM	HYLEBOS WATERWAY	PIERCE 24
WA-0038679	LILYBLAD PETRO INC.	BLAIR WATERWAY	PIERCE 25
WA-0003387	MOBIL OIL CORP	INNER COMMENCEMENT BAY	PIERCE 26
WA-0037419	NALLEY'S FINE FOODS	TACOMA STORM SEWER	PIERCE 27
WA-0001252	PACIFIC NORTHERN OIL	CITY WATERWAY	PIERCE 28
WA-0038601	PACIFIC RESINS & CHEMICAL	SITCUM WATERWAY VIA T. ST. SEWER	PIERCE 29

NPDES Permitted Dischargers to Puget Sound

Permit No.	Discharger	Receiving Water	Map ID No.
WA-0003115	PENNWALT CORP	HYLEBOS WATERWAY	PIERCE 30
WA-0003620	PUGET SOUND PLYWOOD INC	INNER COMMENCEMENT BAY	PIERCE 31
WA-0001589	PUREX CORP	SITCUM WATERWAY INNER COMMENCEMENT	PIERCE 32
WA-0003212	ST REGIS PAPER CO	COMMENCEMENT BAY ST PAUL WATERWAY	PIERCE 33
WA-0003221	ST. REGIS PAPER CO.	CITY WATERWAY	PIERCE 34
WA-0001562	REICHHOLD CHEMICALS	BLAIR WATERWAY COMMENCEMENT BAY	PIERCE 35
WA-0001210	SHELL OIL CO	INNER COMMENCEMENT BAY CITY WATRWY	PIERCE 36
WA-0003204	SOUND REFINING CO	HYLEBOS WATERWAY	PIERCE 37
WA-0001490	STAUFFER CHEM CO	BLAIR WATERWAY	PIERCE 38
WA-0000728	UNION OIL OF CA	INNER COMMENCEMENT BAY VIA CITY WW	PIERCE 39
WA-0001783	U.S. OIL & REFINING CO	BLAIR WATERWAY VIA DRAINAGE DITCH	PIERCE 40
WA-0037893	WESTSIDE WATER DISTRICT	PUGET SOUND NARROWS	PIERCE 41
WA-0037125	ZIDELL DISMANTLING INC	HYLEBOS WATERWAY	PIERCE 42
WA-0021954	DEPT OF THE ARMY	PUGET SOUND	PIERCE 43
WA-0000850	ST. REGIS PAPER CO	COMMENCEMENT BAY	PIERCE 44
WA-0037061	CITY OF OLYMPIA	BUDD INLET	THURSTON 1
WA-0038067	BEVERLY BEACH UTILITIES	BUDD INLET	THURSTON 2
WA-0037915	CARLYON BEACH COUNTRY CLB	SQUAXIN PASSAGE	THURSTON 3
WA-0001015	CASCADE POLE CO	BUDD INLETT	THURSTON 4
WA-0021547	DELSON LUMBER CO	BUDD INLET	THURSTON 5
WA-0037940	HUSTON OYSTER CO	MUD BAY	THURSTON 6
WA-0038407	NAT'L FISH & OYSTER	HOGUM BAY	THURSTON 7
WA-0037273	SEASHORE VILLA MOBILE HOM	BUDD INLETT	THURSTON 8
WA-0038717	STANDARD OIL CO OF CA	BUDD INLET	THURSTON 9
WA-0037290	THURSTON CO. PUBLIC WORKS	BUDD INLET	THURSTON 10
WA-0001236	CONTINENTAL CAN CO.	HENDERSON INLET	THURSTON 11
WA-0001708	GEORGIA PACIFIC CORP	HENDERSON INLET	THURSTON 12
WA-0038822	LACEY CO-PLY ASSOC., INC	HENDERSON INLET	THURSTON 13
WA-0023761	HAMA HAMA CO.	HOOD CANAL	MASON 1
WA-0038377	MASON COUNTY PUBLIC WORKS	CASE INLET	MASON 2
WA-0039195	CITY OF TACOMA DEPT P.W.	HOOD CANAL	MASON 3
WA-0003476	ITT RAYONIER INC	HOOD CANAL	MASON 4
WA-0023345	CITY OF SHELTON	OAKLAND BAY	MASON 5
WA-0038563	CITY OF SHELTON	OAKLAND BAY	MASON 6
WA-0038083	CALM COVE OYSTER CO	TOTTEN INLET	MASON 7

NPDES Permitted Dischargers to Puget Sound

Permit No.	Discharger	Receiving Water	Map ID No.
WA-0003484	ITT RAYONIER	OAKLAND BAY	MASON 8
WA-0020745	JOHN A SELLS OYSTER HOUSE	TOTTEN INLET	MASON 9
WA-0037133	OLYMPIA OYSTER CO.	TOTTEN INLET	MASON 10
WA-0038075	RUSTLEWOOD MASON CO PU WK	PICKERING PASSAGE PUGET SOUND	MASON 11
WA-0003174	SIMPSON TIMBER CO	OAKLAND BAY	MASON 12
WA-0003166	SIMPSON TIMBER CO	OAKLAND BAY	MASON 13
WA-0003182	SIMPSON TIMBER CO	OAKLAND BAY	MASON 14
WA-0003158	SIMPSON TIMBER	OAKLAND BAY	MASON 15
WA-0003191	SIMPSON TIMBER	OAKLAND BAY	MASON 16
WA-0021491	SKOOKUM BAY OYSTER CO	SKOOKUM INLET	MASON 17
WA-0037907	UNION OIL CO OF CAL	OAKLAND BAY	MASON 18
WA-0037753	ALDERBROOK INN	HOOD CANAL	MASON 19
WA-0038059	PENINSUL PLYWOOD	PORT ANGELES	CLALLAM 1
WA-0024279	COAST GUARD	PORT ANGELES BAY	CLALLAM 2
WA-0023973	CITY OF PORT ANGELES	ST. JUAN DE FUCA	CLALLAM 3
WA-0037842	M&R TIMBER	PORT ANGELES	CLALLAM 4
WA-0002798	CITY OF PORT ANGELES	PORT ANGELES	CLALLAM 5
WA-0002925	CROWN ZELLERBACH CORP	PORT ANGELES	CLALLAM 6
WA-0000795	ITT RAYONIER INC	PORT ANGELES	CLALLAM 7
WA-0029289	CITY OF BREMERTON	SINCLAIR INLET	KITSAP 1
WA-0029271	CITY OF BREMERTON	PORT WASHINGTON	KITSAP 2
WA-0023256	KITSAP CO PUB WKS-SUQUAM.	PORT MADISON	KITSAP 3
WA-0020907	CITY OF WINSLOW	PUGET SOUND	KITSAP 4
WA-0029661	KITSAP CO SEWER DIST # 5	SINCLAIR INLET	KITSAP 5
WA-0023701	MANCHESTER WASTEWATER TP	PUGET SOUND	KITSAP 6
WA-0023264	KITSAP CO. BOARD/COMMISSR	APPLETREE COVE, PUGET SOUND	KITSAP 7
WA-0022292	POPE & TALBOT, INC.	HOOD CANAL	KITSAP 8
WA-0020346	CITY OF PORT ORCHARD	SINCLAIR INLET	KITSAP 9
WA-0030317	KITSAP CO. SEWER DIST #7	RICH PASSAGE	KITSAP 10
WA-0030520	KITSAP CO DEPT PUBLIC WKS	PORT ORCHARD BAY, PUGET SOUND	KITSAP 11
WA-0023469	MESSENGER HOUSE	PUGET SOUND	KITSAP 12
WA-0030333	LYNWOOD CENTER	RICH PASSAGE	KITSAP 13
WA-0029149	BLAKE ISLAND STATE PARK	EAST PASSAGE, PUGET SOUND	KITSAP 14
WA-0030449	DOMSEA FARMS INC.	RICH PASSAGE	KITSAP 15
WA-0021971	NAVAL TORPEDO & POLARIS M	HOOD CANAL	KITSAP 16
WA-0021989	NAVAL TORPEDO STATION	LIBERTY BAY	KITSAP 17

NPDES Permitted Dischargers to Puget Sound

Permit No.	Discharger	Receiving Water	Map ID No.
WA-0002062	PUGET SD NAVAL SHIP YARD	SINCLAIR INLET	KITSAP 18
WA-0002780	NAVAL SUPPLY CENTER	PUGET SOUND	KITSAP 19
WA-0025194	EPA MANCHESTER LAB	CLAM BAY	KITSAP 20
WA-0021997	NAVAL TORPEDO STATION	PORT TOWNSEND BAY	KITSAP 21
WA-0030309	COUNTRY CLUB OF SEATTLE	PUGET SOUND	KITSAP 22
WA-0001163	COAST OYSTER CO	LIBERTY BAY	KITSAP 23
WA-0038962	SEA FARMS	HOOD CANAL	JEFFERSON 1
WA-0021202	POPE AND TALBOT DEVEL	PUGET SOUND	JEFFERSON 2
WA-0037052	PORT TOWNSEND	ST. OF JUAN DE FUCA	JEFFERSON 3
WA-0000922	CROWN ZELLERBACH CORP	GLEN COVE	JEFFERSON 4
WA-0039080	UNION WHARF CORP	ST. OF JUAN DE FUCA	JEFFERSON 5
WA-0039098	COAST OYSTER CO	QUILCENE BY	JEFFERSON 6

APPENDIX C

Characteristics of Rivers Flowing into Puget Sound. Length and Area of Watershed are Estimated

Name	WDF#	County	Km Length	Km^2 Watershed Area	Gage Location
Unnamed (UN)	01-0001	Whatcom	2.6	7	
Dakota Creek	01-0002	Whatcom	17.7	75	
UN	01-0044	Whatcom	1.9	1	
California Creek	01-0045	Whatcom	11.7	59	
UN	01-0085	Whatcom	2.6	4	
Drainage Ditch	01-0086	Whatcom	3.5	9	
UN	01-0087	Whatcom	2.6	9	
Terrell Creek	01-0089	Whatcom	14.0	23	
UN	01-0100	Whatcom	1.6	2	
UN	01-0101	Whatcom	1.6	2	
Drainage Ditch	01-0102	Whatcom	3.2	8	
UN	01-0103	Whatcom	3.7	4	
Lummi River	01-0104	Whatcom	8.4	58	
UN	01-0118	Whatcom	1.6	2	
Nooksack River	01-0120	Whatcom	129.1	2,141	Ferndale[a]
UN	01-0547	Whatcom	2.1	2	
Squalicum Creek	01-0552	Whatcom	15.6	57	
Whatcom Creek	01-0566	Whatcom	26.2	—	b
Padden Creek	01-0622	Whatcom	6.9	10	
Chuckanut Creek	01-0626	Whatcom	10.5	26	
UN	01-0632	Whatcom	1.6	1	
UN	01-0633	Whatcom	1.6	1	
UN	01-0634	Whatcom	<1.6	1	
UN	01-0635	Whatcom	1.6	1	
UN	01-0636	Whatcom	<1.6	0	
UN	01-0637	Whatcom	<1.6	0	
Oyster Creek	01-0638	Whatcom	7.9	20	
UN	01-0647	Whatcom	<1.6	1	
Colony Creek	01-0648	Whatcom	9.0	22	
Edison Slough	03-0001	Skagit	13.4	34	
Samish River	03-0005	Skagit	46.9	275	Burlington[a]
Drainage Ditch	03-0086	Skagit	33.2	—	
Joe Leary Slough	03-0087	Skagit	10.6	27	
UN	03-0096	Skagit	3.2	8	
UN	03-0100	Skagit	<1.6	4	
Indian Slough	03-0102	Skagit	11.1	28	
Drainage Ditch	03-0115	Skagit	4.0	10	
UN	03-0116	Skagit	1.6	4	
UN	03-0118	Skagit	2.6	7	
Higgins Slough	03-0121	Skagit	3.2	8	
UN	03-0132	Skagit	1.9	5	
UN	03-0135	Skagit	2.6	7	
UN	03-0140	Skagit	7.6	19	
UN	03-0153	Skagit	4.8	12	
UN	03-0155	Skagit	4.6	12	
UN	03-0156	Skagit	3.1	8	
UN	03-0157	Skagit	1.6	4	
UN	03-0159	Skagit	3.9	10	
Sullivan Slough	03-0162	Skagit	2.2	6	
Drainage Ditch	03-0166	Skagit	9.7	25	
Drainage Ditch	03-0167	Skagit	9.7	25	
Hall Slough	03-0168	Skagit	1.9	5	
Drainage Ditch	03-0169	Skagit	8.1	21	
Drainage Ditch	03-0170	Skagit	8.1	—	
Wiley Slough	03-0171	Skagit	4.8	—	
Skagit River	03-0176	Skagit	261.3	>8,011	Mt Vernon[a]
UN	03-2949	Snohomish	10.1	—	
Douglas Slough	03-2972	Snohomish	2.4	—	
Stillaguamish River	05-0001	Snohomish	113.0	1,772	a
Old Stillaguamish	05-0005	Snohomish	13.4	—	
West Pass	05-0006	Snohomish	2.1	—	
UN	05-0449	Snohomish	6.8	68	
UN	05-0455	Snohomish	3.7	41	
UN	05-0456	Snohomish	4.7	27	
UN	05-0457	Snohomish	3.2	31	
UN	06-0001	Island	3.9	4	
UN	06-0002	Island	4.0	5	
UN	06-0006	Island	2.7	7	
UN	06-0011	Island	5.5	10	
UN	06-0015	Island	2.1	3	
UN	06-0020	Island	1.8	3	
UN	06-0022	Island	1.8	3	
UN	06-0023	Island	1.8	1	
UN	06-0024	Island	2.6	8	
UN	06-0025	Island	3.9	7	
UN	06-0026	Island	3.1	8	
UN	06-0029	Island	6.4	31	
UN	06-0037	Island	6.6	14	
UN	06-0044	Island	1.9	3	
UN	06-0046	Island	2.9	4	
UN	06-0049	Island	2.1	3	
UN	06-0052	Island	1.6	3	
UN	06-0053	Island	3.9	8	
UN	06-0055	Island	4.5	8	
UN	06-0056	Island	3.1	5	
UN	06-0057	Island	1.9	3	
Drainage Ditch	06-0061	Island	3.2	3	
UN	06-0062	Island	2.6	10	
UN	06-0064	Island	1.9	3	
UN	06-0068	Island	2.3	3	
UN	06-0069	Island	3.1	5	
UN	06-0070	Island	2.9	4	
UN	06-0071	Island	2.7	5	
UN	06-0073	Island	2.6	4	
UN	06-0075	Island	3.4	8	
Tulalip Creek	07-0001	Snohomish	8.9	31	
Mission Creek	07-0005	Snohomish	9.8	21	
Snohomish River	07-0012	Snohomish	132.7	>4,323	Monroe[a]
Ebey Slough	07-0043	Snohomish	20.0	39	
Steamboat Slough	07-0015	Snohomish	10.0	23	

APPENDIX C (Continued)

Name	WDF#	County	Km Length	Km^2 Watershed Area	Gage Location
Pigeon Creek #1	07-1722	Snohomish	3.5	5	
Pigeon Creek #2	07-1723	Snohomish	2.1	3	
Merrill & Ring Creek	07-1725	Snohomish	4.7	6	
Powder Mill Creek	07-1727	Snohomish	2.9	4	
Jap Gulch	07-1729	Snohomish	2.4	4	
Big Gulch Creek	08-0001	King	2.1	--	
Picnic Creek	08-0004	King	3.5	--	
Norma Creek	08-0005	King	1.8	2	
Lunds Gulch	08-0006	King	3.1	7	
Shell Creek	08-0009	King	2.6	--	
Shelleberger Creek	08-0010	King	1.9	--	
Hidden Lake	08-0017	King	2.2	5	
Pipers Creek	08-0020	King	2.2	5	
Lake Wa. Ship Canal	08-0028	King	15.1	1,572	
Duwamish River	09-0001	King	150.7	1,140	Tukwilla[a]
Longfellow Creek	09-0359	King	2.4	4	
UN	09-0361	King	<1.6	2	
UN	09-0362	King	3.1	6	
Miller Creek	09-0371	King	7.7	17	
Bow Lake Creek	09-0377	King	5.6	21	
UN	09-0380	King	3.1	5	
UN	09-0381	King	2.3	5	
UN	09-0385	King	1.8	2	
UN	09-0386	King	2.1	3	
Joes Creek	10-0001	Pierce	2.3	--	
UN	10-0003	Pierce	1.8	--	
Hylebos Creek	10-0006	Pierce	14.5	39	
Wapato Creek	10-0017	Pierce	22.4	14	
Puyallup River	10-0021	Pierce	87.6	>2,455	Puyallup[a]
UN	11-0001	Pierce	2.4	3	
Nisqually River	11-0008	Pierce	126.4	1,844	Nisqually[a]
McAllister Creek	11-0324	Pierce	8.9	21	
Eaton Creek	11-0330	Pierce	4.7	--	
UN	12-0001	Pierce	1.6	--	
Chambers Creek	12-0007	Pierce	29.9	280	
Sequalitchew Creek	12-0019	Pierce	15.5	99	
UN	13-0002	Thurston	1.9	3	
UN	13-0005	Thurston	2.4	3	
Woodland Creek	13-0006	Thurston	17.7	64	
Woodward Creek	13-0012	Thurston	12.1	22	
Libbey Creek	13-0015	Thurston	1.8	2	
Adams Creek	13-0018	Thurston	2.9	12	
Ellis Creek	13-0022	Thurston	1.8	5	
Mission Creek	13-0025	Thurston	2.4	2	
Indian Creek	13-0026	Thurston	5.3	12	
Deschutes River	13-0028	Thurston	84.0	--	Rainier[a]
UN	13-0133	Thurston	5.8	7	
McLane Creek	13-0138	Thurston	9.0	30	
Perry Creek	14-0001	Thurston	7.2	--	
UN	14-0005	Thurston	1.6	2	
UN	14-0006	Thurston	1.9	1	
Schneider Creek	14-0009	Thurston	8.5	--	
Kennedy Creek	14-0012	Mason	15.5	--	
Skookum Creek	14-0020	Mason	14.5	--	
UN	14-0026	Mason	1.6	2	
UN	14-0027	Mason	1.9	1	
Mill Creek	14-0029	Mason	25.8	>31	
Goldsborough Creek	14-0035	Mason	22.5	44	
Shelton Creek	14-0044	Mason	4.2	4	
Johns Creek	14-0049	Mason	13.4	8	
Cranberry Creek	14-0051	Mason	15.1	35	
Deer Creek	14-0057	Mason	13.7	29	
Malaney Creek	14-0067	Mason	4.7	10	
Uncle John Creek	14-0068	Mason	3.1	2	
Campbell Creek	14-0069	Mason	7.2	18	
UN	14-0074	Mason	1.6	--	
UN	14-0079	Mason	2.4	--	
Jones Creek	14-0080	Mason	2.9	--	
UN	14-0083	Mason	1.6	--	
UN	14-0084	Mason	2.4	--	
UN	14-0087	Mason	2.9	--	
UN	14-0093	Mason	1.6	1	
Sherwood Creek	14-0094	Mason	29.5	39	
UN	14-0110	Mason	2.6	--	
UN	14-0114	Mason	1.6	--	
UN	14-0115	Mason	2.6	--	
UN	14-0117	Mason	2.4	--	
Jarrell Creek	14-0122	Mason	2.3	--	
UN	14-0124	Mason	2.1	--	
UN	14-0126	Mason	1.9	1	
UN	14-0127	Mason	2.7	2	
UN	14-0132	Mason	1.9	1	
Twanoh Creek	14-0134	Mason	2.1	2	
Alderbrook Creek	14-0138	Mason	2.1	--	
UN	15-0001	Pierce	1.9	1	
Coulter Creek	15-0002	Pierce	12.9	31	
UN	15-0012	Pierce	1.9	2	
UN	15-0014	Pierce	2.1	1	
Rocky Creek	15-0015	Pierce	8.1	34	
UN	15-0023	Pierce	1.6	1	
Dutcher Creek	15-0026	Pierce	2.9	1	
UN	15-0028	Pierce	1.9	1	
UN	15-0029	Pierce	2.7	2	
UN	15-0036	Pierce	2.1	2	
Warren Creek	15-0072	Pierce	1.8	1	
Artondale Creek	15-0075	Pierce	3.5	4	b
UN	15-0080	Pierce	2.3	5	
Sullivan Gulch	15-0087	Pierce	1.9	1	
Lackey Creek	15-0046	Pierce	4.0	5	
Minter Creek	15-0048	Pierce	10.1	14	
Burley Creek	15-0056	Pierce	8.4	16	
Purdy Creek	15-0060	Pierce	5.8	8	b
UN	15-0063	Pierce	1.6	1	
McCormick Creek	15-0065	Pierce	2.5	4	b

APPENDIX C (Continued)

Name	WDF#	County	Km Length	Km^2 Watershed Area	Gage Location
UN	15-0068	Pierce	2.4	2	
North Creek	15-0097	Pierce	2.3	--	b
Crescent Creek	15-0099	Pierce	5.0	--	b
Olalla Creek	15-0107	Kitsap	6.8	18	
UN	15-0121	King	1.9	--	
UN	15-0123	King	2.7	--	
UN	15-0126	King	1.6	2	
Judd Creek	15-0129	King	4.7	11	c
UN	15-0139	King	3.7	8	
Tahlequah Creek	15-0147	King	1.9	1	
UN	15-0159	King	4.5	6.5	
UN	15-0173	King	1.8	--	
UN	15-0183	Kitsap	1.8	1	
Curley Creek	15-0185	Kitsap	8.5	16	
Beaver Creek	15-0192	Kitsap	3.9	3	
UN	15-0193	Kitsap	2.3	2	
UN	15-0196	Kitsap	1.9	3	
Wilson Creek	15-0201	Kitsap	2.9	2	
Annapolis Creek	15-0202	Kitsap	1.9	1	
Blackjack Creek	15-0203	Kitsap	11.1	23	
Ross Creek	15-0209	Kitsap	2.3	3	
Anderson Creek	15-0211	Kitsap	2.9	4	
UN	15-0215	Kitsap	2.1	2	
Gorst Creek	15-0216	Kitsap	6.3	21	
UN	15-0225	Kitsap	1.9	2	
UN	15-0226	Kitsap	1.9	2	
Chico Creek	15-0229	Kitsap	9.7	31	c
Koch Creek	15-0245	Kitsap	2.3	2	
Strawberry Creek	15-0246	Kitsap	4.0	2	
Clear Creek	15-0249	Kitsap	5.2	9	
Barker Creek	15-0255	Kitsap	5.2	4	
UN	15-0258	Kitsap	1.6	1	
Illahee Creek	15-0266	Kitsap	2.3	--	
UN	15-0269	Kitsap	1.8	7	
UN	15-0272	Kitsap	1.8	7	
Steele Creek	15-0273	Kitsap	3.4	9	
UN	15-0278	Kitsap	1.6	2	
Little Scandia Creek	15-0279	Kitsap	2.9	3	
Big Scandia Creek	15-0280	Kitsap	3.5	2	
UN	15-0283	Kitsap	1.6	4	
Dogfish Creek	15-0285	Kitsap	5.6	12	
UN	15-0290	Kitsap	2.4	1	
UN	15-0291	Kitsap	3.1	4	
UN	15-0293	Kitsap	2.9	3	
UN	15-0296	Kitsap	2.7	4	
Grovers Creek	15-0299	Kitsap	8.2	16	
UN	15-0306	Kitsap	1.8	2	
UN	15-0307	Kitsap	1.9	2	
UN	15-0308	Kitsap	2.4	3	
UN	15-0309	Kitsap	4.7	2	
UN	15-0310	Kitsap	2.4	3	

Name	WDF #	County	Km Length	Km^2 Watershed Area	Gage Location
Eglon Creek	15-0311	Kitsap	2.5	8	
UN	15-0313	Kitsap	2.2	2	
UN	15-0316	Kitsap	2.4	5	
UN	15-0317	Kitsap	2.3	5	
UN	15-0320	Kitsap	1.8	3	
UN	15-0321	Kitsap	2.1	7	
UN	15-0324	Kitsap	2.7	4	
UN	15-0325	Kitsap	1.6	3	
UN	15-0340	Kitsap	3.2	8	
UN	15-0344	Kitsap	2.6	3	
UN	15-0347	Kitsap	2.7	4	
UN	15-0348	Kitsap	3.1	5	
UN	15-0349	Kitsap	2.9	6	
UN	15-0350	Kitsap	2.4	3	
UN	15-0353	Kitsap	3.4	8	
Gamble Creek	15-0356	Kitsap	7.9	13	
Todhunter Creek	15-0360	Kitsap	2.1	4	
UN	15-0361	Kitsap	1.6	1	
UN	15-0364	Kitsap	2.1	6	
UN	15-0367	Kitsap	3.1	3	
Jumpoff Joe Creek	15-0369	Kitsap	2.6	4	
UN	15-0370	Kitsap	2.7	5	
UN	15-0371	Kitsap	2.1	3	
UN	15-0376	Kitsap	2.3	4	
Little Anderson Creek	15-0377	Kitsap	3.2	19	
Johnson Creek	15-0387	Kitsap	2.3	2	
Big Beef Creek	15-0389	Kitsap	16.1	40	c
Little Beef Creek	15-0399	Kitsap	1.6	1	
Seabeck Creek	15-0400	Kitsap	5.8	11	
Stavis Creek	15-0404	Kitsap	6.8	10	
Boyce Creek	15-0407	Kitsap	3.5	2	
UN	15-0408	Kitsap	1.6	1	
Anderson Creek	15-0412	Kitsap	6.3	12	
Dewatto River	15-0420	Kitsap	14.0	62	c
UN	15-0438	Kitsap	2.9	2	
Rendsland Creek	15-0439	Kitsap	8.5	19	
UN	15-0444	Kitsap	1.8	1	
Caldervin Creek	15-0445	Kitsap	2.4	2	
Tahuya River	15-0446	Kitsap	34.0	140	
Shoofly Creek	15-0478	Kitsap	2.4	2	
Stimson Creek	15-0488	Kitsap	8.5	1	
UN	15-0492	Kitsap	1.9	2	
Little Mission Creek	15-0493	Kitsap	3.4	6	
Big Mission Creek	15-0495	Kitsap	15.9	53	
Union River	15-0503	Kitsap	15.6	61	
Skokomish River	16-0001	Mason	67.5	622	Potlatch[a]
UN	16-0215	Mason	2.9	2	
UN	16-0216	Mason	2.7	3	
UN	16-0217	Mason	1.6	1	
UN	16-0218	Mason	2.3	2	
UN	16-0220	Mason	2.3	2	

APPENDIX C (Continued)

Name	WDF#	County	Km Length	Km^2 Watershed Area	Gage Location
Hill Creek	16-0221	Mason	1.6	1	
Finch Creek	16-0222	Mason	5.3	5	
Clark Creek	16-0224	Mason	2.3	2	
Miller Creek	16-0225	Mason	4.3	4	
Sund Creek	16-0226	Mason	4.3	6	
Little Lilliwaup Creek	16-0228	Mason	1.6	2	
Lilliwaup River	16-0230	Mason	11.1	31	
Eagle Creek	16-0243	Mason	5.2	18	
Jorsted Creek	16-0248	Mason	6.1	10	
Hamma Hamma River	16-0251	Mason	28.7	219	
Waketicken Creek	16-0318	Mason	10.6	18	
UN	16-0325	Mason	2.6	1	
Schaerer Creek	16-0326	Mason	2.9	3	
Fulton Creek	16-0332	Jefferson	9.0	29	
McDonald Creek	16-0349	Jefferson	3.1	2	
Duckabush River	16-0351	Jefferson	38.8	172	c
Pierce Creek	16-0438	Jefferson	2.6	1	
UN	16-0439	Jefferson	2.3	1	
Walker Creek	16-0441	Jefferson	2.7	2	
Dosewallips River	16-0442	Jefferson	45.6	114	
Turner Creek	16-0559	Jefferson	1.9	1	
Marple Creek	17-0001	Jefferson	3.9	12	
Spencer Creek	17-0004	Jefferson	6.1	7	
UN	17-0007	Jefferson	4.2	6	
UN	17-0011	Jefferson	2.7	3	
Big Quilcene River	17-0012	Jefferson	30.4	238	Quilcene
Little Quilcene River	17-0076	Jefferson	19.6	91	
Donovan Creek	17-0115	Jefferson	4.8	16	
UN	17-0123	Jefferson	2.1	2	
UN	17-0128	Jefferson	1.6	1	
Tarbo Creek	17-0129	Jefferson	10.9	32	
UN	17-0141	Jefferson	3.4	3	
UN	17-0147	Jefferson	1.6	--	
UN	17-0156	Jefferson	1.6	--	
UN	17-0159	Jefferson	1.6	--	
UN	17-0161	Jefferson	2.1	--	
UN	17-0163	Jefferson	2.3	--	
UN	17-0166	Jefferson	1.9	2	
UN	17-0167	Jefferson	4.3	6	
Thorndyke Creek	17-0170	Jefferson	10.1	31	
UN	17-0180	Jefferson	2.3	2	
Shine Creek	17-0181	Jefferson	3.2	3	
UN	17-0190	Jefferson	1.9	3	
Ludlow Creek	17-0192	Jefferson	7.2	25	
UN	17-0200	Jefferson	2.3	4	
Chimacum Creek	17-0203	Jefferson	22.9	87	Hadlock
McDonald Creek	18-0160	Clallam	21.9	60	
Siebert Creek	18-0173	Clallam	20.0	51	
Bagley Creek	18-0183	Clallam	11.3	20	
Morse Creek	18-0185	Clallam	26.2	--	c
Lees Creek	18-0232	Clallam	14.0	--	
Ennis Creek	18-0234	Clallam	6.9	--	
Peabody Creek	18-0245	Clallam	7.7	--	
Valley Creek	18-0249	Clallam	7.9	--	
Tumwater Creek	18-0256	Clallam	8.2	697	
Elwha River	18-0272				McDonald Bridge[a]

NOTES: [a] = See Table 4-1 for water quality data.
[b] = Limited water quality data, but no flow data.
[c] = Flow data, but no water quality data.

Appendix D. Mass Loading Values Calculated From Available Data

The following 14 tables summarize mass loading values for pollutants in various regions or subareas of Puget Sound, and the Straits of Georgia and Juan de Fuca. There are several features about these tables that must be considered.

- The study area is broken down into regions and subareas. The subareas were selected as localized water bodies in which separate mass loading values would be of use to water quality managers. Although these subareas are located in certain regions of Puget Sound, the mass loading data for these subareas are not included in the mass loading data for the region as a whole.

- Caution is suggested when viewing the mass loading values in Appendix D. These values should not be considered as total pollutant loading estimates since the values represent estimates obtained through monitoring programs that may not have surveyed all of the pollutants in the effluent. As an estimate of monitoring thoroughness, the number of dischargers contributing to each loading value is provided, as is the total number of dischargers. Furthermore, the frequency of monitoring was quite low for most pollutants, thereby limiting the accuracy of the estimates.

- The calculations were made by multiplying the concentration (usually in mg/l) by the average daily discharge. The calculated values were rounded off to the whole kilogram where possible, or to the tenth (0.1) or hundredth (0.01) kilogram. Values calculated to be less than 0.005 kg/d are shown as <0.01 kg/day.

- Loading values often are reported as less than a given value. The "<" symbol denotes those cases where only a maximum value was reported for a discharge and where the calculated mass loading is <0.01 kg/day. Caution is suggested since all of the potential loadings may not have been monitored. Mass loadings reported as "t" indicate a pollutant that was identified, but not quantified. In many cases, pollutants were not detected and denoted in the appendix by "ND". The threshold concentration of detection was usually 0.01 mg/l, but may have been as high as 0.25 mg/l.

- The values shown are average daily loadings obtained from surveys conducted from 1979 to present. Data from the most recent year were used when more than 1 year of data were available. Where possible, values for wet and dry seasons are reported. The annual average daily loading is a weighted mean of the average daily loading for the 7 wet months and 5 dry months. If only wet or dry season

data were available, the annual average daily load was assumed to be equal to the average daily load for the reported season.

- Totals are provided only when data are available from municipal and industrial dischargers, or permitted and nonpermitted sources. The number of values contributing to the total value is equal to the sum of the dischargers providing mass loading data.

- The mass loading values for municipal and industrial dischargers were obtained from nearly every available NPDES monitoring survey. Since NPDES permit limitations indicated that certain monitoring surveys would include at best a few conventional parameters, no special effort was made to locate and obtain data for a few, small, minor dischargers.

Appendix D. Mass loading values calculated from available data. Number of sources contributing to each calculated value is shown in parentheses. Data for all values are given in kg/day, except where noted.

Receiving Water Strait of Georgia	Municipal (3) Wet	Municipal (3) Dry	Municipal (3) Annual	Industrial (7) Wet	Industrial (7) Dry	Industrial (7) Annual	Total for NPDES Permitted Dischargers Wet	Total for NPDES Permitted Dischargers Dry	Total for NPDES Permitted Dischargers Annual	Nonpermitted Sources Annual	Grand Total Annual
CONVENTIONAL POLLUTANT											
Flow (cubic m/d)	3,182	1,356	2,417 (2)	54,333	29,636	43,902 (4)	57,515	30,992	46,319		
Biochemical Oxygen Demand (BOD)	53	18	39 (2)	221	238	223 (3)	274	256	267		
Total Suspended Solids	34	14	26 (2)	1,148	873	1,033 (3)	1,182	887	1,059		
Oils & Grease				163	143	155 (3)					
pH (range)	6.9-7.7	6.7-7.6	6.7-7.7 (2)	6.1-9.8	6.1-9.4	6.1-9.8 (3)	6.1-9.8	6.1-9.4	6.1-9.8		
Fecal Coliform (MPN/100 ml)	1-134	19-146	1-146 (2)	6-100	5-100	5-100 (3)	1-134	5-146	1-146		
EXTENDED CONVENTIONAL POLLUTANT											
Chemical Oxygen Demand (COD)			(0)	2,890	1,922	2,487 (3)					
Total Solids			(0)			(0)					
Total Nonvolatile Solids			(0)			(0)					
Total Nonvolatile Suspended Solids			(0)			(0)					
Total Nitrogen			(0)			315 (3)					
Total Phosphorus			(0)			6 (2)					
PRIORITY POLLUTANT											
Heavy Metals & Inorg.											
Antimony			(0)			0.7 (3)					
Arsenic			(0)			0.2 (3)					
Asbestos (fibers/d)			(0)			(0)					
Beryllium			(0)			0.1 (3)					
Cadmium			(0)			0.1 (3)					
Chromium			(0)	2	0.8	1 (3)					
Copper			(0)			1 (3)					
Cyanide			(0)	3	2	2 (3)					
Lead			(0)			0.3 (3)					
Mercury			(0)			0.02 (3)					
Nickel			(0)			1 (3)					
Selenium			(0)			0.3 (3)					
Silver			(0)			0.1 (3)					
Thallium			(0)			0.01 (3)					
Zinc			(0)			4 (3)					
Pesticides, PCBs, etc.											
Acrolein			(0)			ND (3)					
Aldrin			(0)			ND (3)					
Chlorodane			(0)			ND (3)					
DDD			(0)			ND (3)					
DDE			(0)			ND (3)					
DDT			(0)			ND (3)					

Dieldrin			(0)			ND	(3)				
Endosulfan and Endosulfan Sulfate			(0)			ND	(3)				
Endrin and Endrin Aldehyde			(0)			ND	(3)				
Heptachlor											
Heptachlor Epoxide			(0)			ND	(3)				
Hexachlorocyclohexane Isomers			(0)			ND	(3)				
Isophorone			(0)			ND	(3)				
TCDD											
Toxaphene			(0)			ND	(3)				
PCBs			(0)			ND	(3)				
2-Chloronaphthalene			(0)			ND	(3)				
			(0)			0.1	(3)				
Halogenated Aliphatic Hydrocarbons											
Methyl Chloride											
Methylene Chloride			(0)			ND	(3)				
Chloroform			(0)			0.8	(3)				
Carbon Tetrachloride			(0)			0.3	(3)				
Chloroethane			(0)			ND	(3)				
1,1-Dichloroethane			(0)			ND	(3)				
1,2-Dichloroethane			(0)			ND	(3)				
1,1,1-Trichloroethane			(0)			0.1	(3)				
1,1,2-Trichloroethane			(0)			0.1	(3)				
1,1,2,2-Tetrachloroethane			(0)			ND	(3)				
Hexachloroethane			(0)			ND	(3)				
Vinyl Chloride											
1,1-Dichloroethylene			(0)			ND	(3)				
1,2-trans-Dichloroethylene			(0)			ND	(3)				
Trichloroethylene			(0)			ND	(3)				
Tetrachloroethylene			(0)			ND	(3)				
1,2-Dichloropropane			(0)			0.1	(3)				
1,3-Dichloropropene			(0)			0.1	(3)				
Hexachlorobutadiene			(0)			0.1	(3)				
Hexachlorocyclopentadiene			(0)			ND	(3)				
Methyl Bromide			(0)			ND	(3)				
Dichlorobromomethane			(0)			ND	(3)				
Chlorodibromomethane			(0)			0.1	(3)				
Bromoform			(0)			ND	(3)				
Dichlorodifluoromethane			(0)			ND	(3)				
Trichlorofluoromethane			(0)			ND	(3)				
			(0)			0.1	(3)				
Halogenated Ethers											
Bis(chloromethyl) Ether			(0)			ND	(3)				
Bis(2-chloroethyl) Ether			(0)			ND	(3)				

Bis(2-chloroiso-propyl) Ether			(0)			ND (3)				
2-chloroethyl Vinyl Ether			(0)			ND (3)				
4-chlorophenyl Phenyl Ether			(0)			ND (3)				
4-Bromophenyl Phenyl Ether			(0)			ND (3)				
Bis(2-chloroethoxy) Methane			(0)			ND (3)				
Monocyclic Aromatics										
Benzene			(0)			0.2 (3)				
Chlorobenzene			(0)			0.1 (3)				
1,2-Dichlorobenzene			(0)			ND (3)				
1,3-Dichlorobenzene			(0)			ND (3)				
1,4-Dichlorobenzene			(0)			ND (3)				
1,2,4-Trichloro-benzene			(0)			ND (3)				
Hexachlorobenzene			(0)			ND (3)				
Ethylbenzene			(0)			0.1 (3)				
Nitrobenzene			(0)			ND (3)				
Toluene			(0)			0.1 (3)				
2,4-Dinitrotoluene			(0)			ND (3)				
2,6-Dinitrotoluene			(0)			ND (3)				
Phenol			(0)			0.1 (3)				
2-Chlorophenol			(0)			ND (3)				
2,4-Dichlorophenol			(0)			ND (3)				
2,4,6-Tricholoro-phenol			(0)			ND (3)				
Pentachlorophenol			(0)			ND (3)				
2-Nitrophenol			(0)			ND (3)				
4-Nitrophenol			(0)			ND (3)				
2,4-Dinitrophenol			(0)			0.1 (3)				
2,4-Dimethyl Phenol			(0)			ND (3)				
p-Chloro-m-cresol			(0)			ND (3)				
4,6-Dinitro-o-cresol			(0)			ND (3)				
Phthalate Esters										
Dimethyl Phthalate			(0)			0.1 (3)				
Diethyl Phthalate			(0)			0.1 (3)				
Di-n-butyl Phthalate			(0)			0.1 (3)				
Di-n-octyl Phthalate			(0)			0.1 (3)				
Bis(2-ethylhexyl) Phthalate			(0)			0.1 (3)				
Butyl Benzyl Phthalate			(0)			0.1 (3)				
Polycyclic Aromatic Hydrocarbons										
Acenaphthene			(0)			ND (3)				
Acenaphthylene			(0)			ND (3)				
Fluorene			(0)			ND (3)				
Napthalene			(0)			0.1 (3)				
Anthracene			(0)			0.1 (3)				

Fluoranthene			(0)			2	(3)				
Phenanthrene			(0)			0.1	(3)				
Benzo[a]anthracene			(0)			0.1	(3)				
Benzo[b]fluoranthene			(0)			0.1	(3)				
Benzo[k]fluoranthene			(0)			ND	(3)				
Chrysene			(0)			0.1	(3)				
Pyrene			(0)			2	(3)				
Benzo[ghi]perylene			(0)			ND	(3)				
Benzo[a]pyrene			(0)			ND	(3)				
Dibenzo[a]anthracene			(0)			ND	(3)				
Indeno[1,2,3-cd]-pyrene			(0)			ND	(3)				
Nitrosamines & Misc.											
N-nitrosodimethyl-amine			(0)			ND	(3)				
N-nitrosodiphenyl-amine			(0)			0.1	(3)				
N-nitrosodi-n-propylamine			(0)			ND	(3)				
Benzidine			(0)			ND	(3)				
3,3'-Dichloro-benzidine			(0)			ND	(3)				
1,2-Diphenylhydrazine			(0)			ND	(3)				
Acrylonitrile			(0)			ND	(3)				

Appendix D. Mass loading values calculated from available data. Number of sources contributing to each calculated value is shown in parentheses. Data for all values are given in kg/day, except where noted.

Receiving Water	Municipal (1) Wet	Municipal (1) Dry	Municipal (1) Annual		Industrial (11) Wet	Industrial (11) Dry	Industrial (11) Annual		Total for NPDES Permitted Dischargers Wet	Total for NPDES Permitted Dischargers Dry	Total for NPDES Permitted Dischargers Annual	Nonpermitted Sources Annual	Grand Total Annual
Bellingham Bay													
CONVENTIONAL POLLUTANT													
Flow (cubic m/d)	53,900	32,348	44,923	(1)	147,156	147,156	147,156	(1)	201,056	179,504	192,079		
Biochemical Oxygen Demand (BOD)	2,645	6,859	4,400	(1)	11,976	8,210	10,406	(1)	14,621	15,069	14,806		
Total Suspended Solids	2,087	2,127	2,105	(1)	17,804	14,266	16,330	(1)	19,891	16,393	18,435		
Oils & Grease				(0)	ND		ND	(1)					
pH (range)	6.3-7.3	4.4-7.2	4.4-7.3	(1)	5.0-6.9	4.8-7.5	4.8-7.5	(1)	5.0-7.3	4.4-7.5	4.4-7.5		
Fecal Coliform (MPN/100 ml)	17-123	9-51	9-123	(1)	2,400	2,400	2,400	(1)	70-2,400	30-2,400	30-2,400		
EXTENDED CONVENTIONAL POLLUTANT													
Chemical Oxygen Demand (COD)				(0)	155,910		155,910	(1)					
Total Solids				(0)				(0)					
Total Nonvolatile Solids				(0)				(0)					
Total Nonvolatile Suspended Solids				(0)				(0)					
Total Nitrogen				(0)	2,089		2,089	(1)					
Total Phosphorus				(0)	176		176	(1)					
PRIORITY POLLUTANT													
Heavy Metals & Inorg.				(0)	ND		ND	(1)					
Antimony				(0)	0.9		0.9	(1)					
Arsenic				(0)				(0)					
Asbestos (fibers/d)				(0)	ND		ND	(1)					
Beryllium				(0)	ND		ND	(1)					
Cadmium				(0)	80		80	(1)					
Chromium				(0)	4		4	(1)					
Copper				(0)	1		1	(1)					
Cyanide				(0)	4		4	(1)					
Lead				(0)	0.02	0.01	0.02	(1)					
Mercury				(0)	2		2	(1)					
Nickel				(0)	1		1	(1)					
Selenium				(0)	2		2	(1)					
Silver				(0)	ND		ND	(1)					
Thallium				(0)	18		18	(1)					
Zinc													
Pesticides, PCBs, etc.													
Acrolein				(0)	ND		ND	(1)					
Aldrin				(0)	ND		ND	(1)					
Chlorodane				(0)	ND		ND	(1)					
DDD				(0)	ND		ND	(1)					
DDE				(0)	ND		ND	(1)					
DDT				(0)	ND		ND	(1)					

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Dieldrin			(0)	ND		ND	(1)				
Endosulfan and Endosulfan Sulfate			(0)	ND		ND	(1)				
Endrin and Endrin Aldehyde			(0)	ND		ND	(1)				
Heptachlor			(0)	ND		ND	(1)				
Heptachlor Epoxide			(0)	ND		ND	(1)				
Hexachlorocyclohexane Isomers			(0)	ND		ND	(1)				
Isophorone			(0)	ND		ND	(1)				
TCDD			(0)	ND		ND	(1)				
Toxaphene			(0)	ND		ND	(1)				
PCBs			(0)	ND		ND	(1)				
2-Chloronaphthalene			(0)	ND		ND	(1)				
Halogenated Aliphatic Hydrocarbons											
Methyl Chloride			(0)	ND		ND	(1)				
Methylene Chloride			(0)	ND		ND	(1)				
Chloroform			(0)	9		9	(1)				
Carbon Tetrachloride			(0)	ND		ND	(1)				
Chloroethane			(0)	ND		ND	(1)				
1,1-Dichloroethane			(0)	ND		ND	(1)				
1,2-Dichloroethane			(0)	ND		ND	(1)				
1,1,1-Trichloroethane			(0)	ND		ND	(1)				
1,1,2-Trichloroethane			(0)	ND		ND	(1)				
1,1,2,2-Tetrachloroethane			(0)	ND		ND	(1)				
Hexachloroethane			(0)	ND		ND	(1)				
Vinyl Chloride			(0)	ND		ND	(1)				
1,1-Dichloroethylene			(0)	ND		ND	(1)				
1,2-trans-Dichloroethylene			(0)	ND		ND	(1)				
Trichloroethylene			(0)	ND		ND	(1)				
Tetrachloroethylene			(0)	ND		ND	(1)				
1,2-Dichloropropane			(0)	ND		ND	(1)				
1,3-Dichloropropene			(0)	ND		ND	(1)				
Hexachlorobutadiene			(0)	ND		ND	(1)				
Hexachlorocyclopentadiene			(0)	ND		ND	(1)				
Methyl Bromide			(0)	ND		ND	(1)				
Dichlorobromomethane			(0)	ND		ND	(1)				
Chlorodibromomethane			(0)	ND		ND	(1)				
Bromoform			(0)	ND		ND	(1)				
Dichlorodifluoromethane			(0)	ND		ND	(1)				
Trichlorofluoromethane			(0)	ND		ND	(1)				
Halogenated Ethers											
Bis(chloromethyl) Ether			(0)	ND		ND	(1)				
Bis(2-chloroethyl) Ether			(0)	ND		ND	(1)				

Bis(2-chloroisopropyl) Ether			(0)	ND		ND	(1)				
2-chloroethyl Vinyl Ether			(0)	ND		ND	(1)				
4-chlorophenyl Phenyl Ether			(0)	ND		ND	(1)				
4-Bromophenyl Phenyl Ether			(0)	ND		ND	(1)				
Bis(2-chloroethoxy) Methane			(0)	ND		ND	(1)				
Monocyclic Aromatics											
Benzene			(0)	ND		ND	(1)				
Chlorobenzene			(0)	ND		ND	(1)				
1,2-Dichlorobenzene			(0)	ND		ND	(1)				
1,3-Dichlorobenzene			(0)	ND		ND	(1)				
1,4-Dichlorobenzene			(0)	ND		ND	(1)				
1,2,4-Trichlorobenzene			(0)	ND		ND	(1)				
Hexachlorobenzene			(0)	ND		ND	(1)				
Ethylbenzene			(0)	ND		ND	(1)				
Nitrobenzene			(0)	ND		ND	(1)				
Toluene			(0)	ND		ND	(1)				
2,4-Dinitrotoluene			(0)	ND		ND	(1)				
2,6-Dinitrotoluene			(0)	ND		ND	(1)				
Phenol			(0)	ND		ND	(1)				
2-Chlorophenol			(0)	ND		ND	(1)				
2,4-Dichlorophenol			(0)	ND		ND	(1)				
2,4,6-Tricholorophenol			(0)	ND		ND	(1)				
Pentachlorophenol			(0)	ND		ND	(1)				
2-Nitrophenol			(0)	ND		ND	(1)				
4-Nitrophenol			(0)	ND		ND	(1)				
2,4-Dinitrophenol			(0)	ND		ND	(1)				
2,4-Dimethyl Phenol			(0)	ND		ND	(1)				
p-Chloro-m-cresol			(0)	ND		ND	(1)				
4,6-Dinitro-o-cresol											
Phthalate Esters											
Dimethyl Phthalate			(0)	ND		ND	(1)				
Diethyl Phthalate			(0)	ND		ND	(1)				
Di-n-butyl Phthalate			(0)	ND		ND	(1)				
Di-n-octyl Phthalate			(0)	ND		ND	(1)				
Bis(2-ethylhexyl) Phthalate			(0)	ND		ND	(1)				
Butyl Benzyl Phthalate			(0)	ND		ND	(1)				
Polycyclic Aromatic Hydrocarbons											
Acenaphthene			(0)	ND		ND	(1)				
Acenaphthylene			(0)	ND		ND	(1)				
Fluorene			(0)	ND		ND	(1)				
Napthalene			(0)	ND		ND	(1)				
Anthracene			(0)	ND		ND	(1)				

Fluoranthene			(0)	ND		ND	(1)				
Phenanthrene			(0)	ND		ND	(1)				
Benzo[a]anthracene			(0)	ND		ND	(1)				
Benzo[b]fluoranthene			(0)	ND		ND	(1)				
Benzo[k]fluoranthene			(0)	ND		ND	(1)				
Chrysene			(0)	ND		ND	(1)				
Pyrene			(0)	ND		ND	(1)				
Benzo[ghi]perylene			(0)	ND		ND	(1)				
Benzo[a]pyrene			(0)	ND		ND	(1)				
Dibenzo[a]anthracene			(0)	ND		ND	(1)				
Indeno[1,2,3-cd]-pyrene			(0)	ND		ND	(1)				
Nitrosamines & Misc.											
N-nitrosodimethyl-amine			(0)	ND		ND	(1)				
N-nitrosodiphenyl-amine			(0)	ND		ND	(1)				
N-nitrosodi-n-propylamine			(0)	ND		ND	(1)				
Benzidine			(0)	ND		ND	(1)				
3,3'-Dichloro-benzidine			(0)	ND		ND	(1)				
1,2-Diphenylhydrazine			(0)	ND		ND	(1)				
Acrylonitrile											

Appendix D. Mass loading values calculated from available data. Number of sources contributing to each calculated value is shown in parentheses. Data for all values are given in kg/day, except where noted.

Receiving Water	Municipal (2) Wet	Municipal (2) Dry	Municipal (2) Annual	Industrial (8) Wet	Industrial (8) Dry	Industrial (8) Annual	Total for NPDES Permitted Dischargers Wet	Total for NPDES Permitted Dischargers Dry	Total for NPDES Permitted Dischargers Annual	Nonpermitted Sources Annual	Grand Total Annual
Anacortes											
CONVENTIONAL POLLUTANT											
Flow (cubic m/d)	7,192	3,523	5,663 (2)	22,537	16,288	19,933 (4)	29,729	19,811	25,596		
Biochemical Oxygen Demand (BOD)	921	689	824 (2)	208	159	187 (2)	1,129	848	1,011		
Total Suspended Solids	327	440	374 (2)	363	227	306 (3)	690	667	680		
Oils & Grease			(0)	93	70	83 (2)					
pH (range)	6.0-7.3	6.5-7.2	6.0-7.3 (2)	6.5-8.9	6.6-8.7	6.5-8.9 (3)	6.0-8.9	6.5-8.7	6.0-8.9		
Fecal Coliform (MPN/100 ml)	10-83	10-58	10-83 (2)	0-4	2-68	0-68 (2)	0-83	2-68	0-68		
EXTENDED CONVENTIONAL POLLUTANT											
Chemical Oxygen Demand (COD)			(0)	1,588	1,283	1,461 (2)					
Total Solids			(0)	357	222	299 (2)					
Total Nonvolatile Solids			(0)			(0)					
Total Nonvolatile Suspended Solids			(0)			(0)					
Total Nitrogen			(0)	167		167 (2)					
Total Phosphorus			(0)	6		6 (2)					
PRIORITY POLLUTANT											
Heavy Metals & Inorg.											
Antimony			<.01 (1)	8		8 (2)			8		
Arsenic			.02 (1)	0.5		0.5 (2)			0.5		
Asbestos (fibers/d)			(0)			(0)					
Beryllium			<.01 (1)	0.2		0.2 (2)			0.2		
Cadmium			0.02 (2)	0.2		0.2 (2)			0.2		
Chromium			0.04 (2)	1	1	1 (2)			1		
Copper			0.7 (2)	1		1 (2)			2		
Cyanide			0.03 (2)	0.6		0.6 (2)			0.6		
Lead			0.2 (2)	5		5 (2)			5		
Mercury			<.01 (2)	0.04		0.04 (2)			0.05		
Nickel			1 (2)	2		2 (2)			3		
Selenium			.03 (2)	0.8		0.8 (2)			0.8		
Silver			<.01 (2)	0.6		0.6 (2)			0.6		
Thallium			<.01 (2)	0.5		0.5 (2)			0.5		
Zinc			0.8 (2)	1		1 (2)			2		
Pesticides, PCBs, etc.											
Acrolein			ND (2)	ND		ND (1)			ND		
Aldrin			ND (1)	ND		ND (1)			ND		
Chlorodane			ND (2)	ND		ND (1)			ND		
DDD			ND (2)	ND		ND (1)			ND		
DDE			<0.01[a] (2)	ND		ND (1)			<0.01		
DDT			ND (2)	ND		ND (1)			ND		

NOTE: a - not confirmed by gas chromatography and mass spectrophotometer.

Dieldrin			ND (1)	ND		ND (1)			ND
Endosulfan and Endosulfan Sulfate			ND (2)	ND		ND (1)			ND
Endrin and Endrin Aldehyde			ND (2)	ND		ND (1)			ND
Heptachlor			ND (2)	ND		ND (1)			ND
Heptachlor Epoxide			ND (2)	ND		ND (1)			ND
Hexachlorocyclohexane Isomers			<0.01[a] (2)	ND		ND (1)			<0.01
Isophorone			ND (2)	ND		ND (1)			ND
TCDD			(0)			(0)			
Toxaphene			ND (2)	ND		ND (1)			ND
PCBs			ND (2)	ND		ND (1)			ND
2-Chloronaphthalene			T (2)	ND		ND (1)			T
Halogenated Aliphatic Hydrocarbons									
Methyl Chloride			ND (2)	ND		ND (2)			ND
Methylene Chloride			0.9 (2)	ND		ND (1)			1
Chloroform			ND (2)	ND		ND (2)			ND
Carbon Tetrachloride			ND (2)	ND		ND (1)			ND
Chloroethane			ND (2)	ND		ND (1)			ND
1,1-Dichloroethane			ND (2)	ND		ND (1)			ND
1,2-Dichloroethane			ND (2)	ND		ND (1)			ND
1,1,1-Trichloroethane			0.5 (2)	ND		ND (2)			0.5
1,1,2-Trichloroethane			ND (2)	ND		ND (1)			ND
1,1,2,2-Tetrachloroethane			(0)	0.08		0.08			0.08
Hexachloroethane			ND (2)	ND		ND (1)			ND
Vinyl Chloride			ND (2)	ND		ND (1)			ND
1,1-Dichloroethylene			ND (2)	ND		ND (1)			ND
1,2-trans-Dichloroethylene			ND (2)	ND		ND (1)			ND
Trichloroethylene			ND (2)	ND		ND (1)			0.3
Tetrachloroethylene			0.3 (2)	ND		ND (1)			ND
1,2-Dichloropropane			ND (2)	ND		ND (1)			ND
1,3-Dichloropropene			ND (2)	ND		ND (1)			ND
Hexachlorobutadiene			ND (2)	ND		ND (1)			ND
Hexachlorocyclopentadiene			ND (2)	ND		ND (1)			ND
Methyl Bromide			ND (2)	ND		ND (1)			ND
Dichlorobromomethane			(0)	ND		ND (1)			ND
Chlorodibromomethane			ND (2)	ND		ND (1)			ND
Bromoform			ND (2)	ND		ND (1)			ND
Dichlorodifluoromethane			ND (2)	ND		ND (1)			ND
Trichlorofluoromethane			ND (2)	ND		ND (1)			ND
Halogenated Ethers									
Bis(chloromethyl) Ether			ND (2)	ND		ND (1)			ND
Bis(2-chloroethyl) Ether			ND (2)	ND		ND (1)			ND

Bis(2-chloroiso-propyl) Ether			ND (2)	ND		ND (1)		ND	
2-chloroethyl Vinyl Ether			ND (1)	ND		ND (1)		ND	
4-chlorophenyl Phenyl Ether			ND (2)	ND		ND (1)		ND	
4-Bromophenyl Phenyl Ether			T (2)	ND		ND (1)		T	
Bis(2-chloroethoxy) Methane			ND (2)	ND		ND (1)		ND	
Monocyclic Aromatics									
Benzene			ND (2)	0.08		0.08 (2)		0.08	
Chlorobenzene			ND (2)	ND		ND (2)		ND	
1,2-Dichlorobenzene			ND (2)	ND		ND (1)		ND	
1,3-Dichlorobenzene			ND (2)	ND		ND (1)		ND	
1,4-Dichlorobenzene			ND (2)	ND		ND (1)		ND	
1,2,4-Trichloro-benzene			ND (2)	ND		ND (1)		ND	
Hexachlorobenzene			T (2)	ND		ND (1)		T	
Ethylbenzene			0.6 (2)	ND		ND (2)		0.6	
Nitrobenzene			ND (2)	ND		ND (1)		ND	
Toluene			0.2 (2)	0.08		0.08 (2)		0.3	
2,4-Dinitrotoluene			ND (2)	ND		ND (1)		ND	
2,6-Dinitrotoluene			ND (2)	ND		ND (1)		ND	
Phenol			0.3 (2)	0.2		0.2 (2)		0.5	
2-Chlorophenol			ND (2)	ND		ND (1)		ND	
2,4-Dichlorophenol			ND (2)	ND		ND (1)		ND	
2,4,6-Tricholoro-phenol			ND (2)	ND		ND (2)		ND	
Pentachlorophenol			0.5 (2)	ND		ND (1)		0.5	
2-Nitrophenol			ND (2)	ND		ND (1)		ND	
4-Nitrophenol			ND (2)	ND		ND (1)		ND	
2,4-Dinitrophenol			ND (2)	ND		ND (1)		ND	
2,4-Dimethyl Phenol			ND (2)	ND		ND (2)		ND	
p-Chloro-m-cresol			T (2)	ND		ND (2)		T	
4,6-Dinitro-o-cresol			ND (2)	ND		ND (1)		ND	
Phthalate Esters									
Dimethyl Phthalate			T (2)	ND		ND (1)		T	
Diethyl Phthalate			T (2)	ND		ND (2)		T	
Di-n-butyl Phthalate			T (2)	ND		ND (1)		T	
Di-n-octyl Phthalate			ND (2)	ND		ND (1)		ND	
Bis(2-ethylhexyl) Phthalate			<0.01 (2)	ND		ND (2)		<0.01	
Butyl Benzyl Phthalate			ND (2)	ND		ND (1)		ND	
Polycyclic Aromatic Hydrocarbons									
Acenaphthene			ND (2)	0.08		0.08 (2)		0.08	
Acenaphthylene			ND (2)	0.08		0.08 (2)		0.08	
Fluorene			T (2)	ND		ND (1)		T	
Napthalene			T (2)	ND		ND (2)		T	
Anthracene			ND (2)	0.08		0.08 (2)		0.08	

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Fluoranthene				ND	(2)	ND		ND	(1)			ND	
Phenanthrene				ND	(2)	0.08		0.08	(2)			0.08	
Benzo[a]anthracene				ND	(2)	ND		ND	(2)			ND	
Benzo[b]fluoranthene				ND	(2)	ND		ND	(1)			ND	
Benzo[k]fluoranthene				ND	(2)	ND		ND	(1)			ND	
Chrysene				ND	(2)	ND		ND	(2)			ND	
Pyrene				ND	(2)	0.08		0.08	(2)			0.08	
Benzo[ghi]perylene				ND	(2)	ND		ND	(1)			ND	
Benzo[a]pyrene				ND	(2)	ND		ND	(1)			ND	
Dibenzo[a]anthracene				ND	(2)	ND		ND	(1)			ND	
Indeno[1,2,3-cd]-pyrene				ND	(2)	ND		ND	(1)			ND	
Nitrosamines & Misc.													
N-nitrosodimethyl-amine				ND	(2)	ND		ND	(1)			ND	
N-nitrosodiphenyl-amine				ND	(2)	ND		ND	(1)			ND	
N-nitrosodi-n-propylamine				ND	(2)	ND		ND	(1)			ND	
Benzidine				ND	(2)	ND		ND	(1)			ND	
3,3'-Dichloro-benzidine				ND	(2)	ND		ND	(1)			ND	
1,2-Diphenylhydrazine				ND	(2)	ND		ND	(1)			ND	
Acrylonitrile				ND	(2)	ND		ND	(1)			ND	

Appendix D. Mass loading values calculated from available data. Number of sources contributing to each calculated value is shown in parentheses. Data for all values are given in kg/day, except where noted.

Receiving Water Whidbey Basin	Municipal (13) Wet	Municipal (13) Dry	Municipal (13) Annual	Industrial (7) Wet	Industrial (7) Dry	Industrial (7) Annual	Total for NPDES Permitted Dischargers Wet	Total for NPDES Permitted Dischargers Dry	Total for NPDES Permitted Dischargers Annual	Nonpermitted Sources Annual[a]	Grand Total Annual
CONVENTIONAL POLLUTANT											
Flow (cubic m/d)	9,291	5,988	7,915 (8)			8 (1)			7,923		
Biochemical Oxygen Demand (BOD)	82	65	233 (7)			16 (1)			249		
Total Suspended Solids	16	56	350 (7)			.7 (1)			351		
Oils & Grease			(0)			(0)					
pH (range)	6.0-7.3	6.5-8.2	6.0-8.2 (9)			(0)					
Fecal Coliform (MPN/100 ml)	0-1,000	6-39,000	0-39,000 (10)			(0)					
EXTENDED CONVENTIONAL POLLUTANT											
Chemical Oxygen Demand (COD)	673		673 (2)			86 (1)			759		
Total Solids	1,737		1,737 (2)			(0)					
Total Nonvolatile Solids	1,353		1,353 (2)			(0)					
Total Nonvolatile Suspended Solids	30		30 (2)			(0)					
Total Nitrogen	73		73 (2)			(0)					
Total Phosphorus	45		45 (2)			(0)					
PRIORITY POLLUTANT											
Heavy Metals & Inorg.											
Antimony			(0)			(0)					
Arsenic			(0)			(0)				71	
Asbestos (fibers/d)			(0)			(0)					
Beryllium			(0)			(0)					
Cadmium			(0)			(0)				68	
Chromium			(0)			(0)				245	
Copper			(0)			(0)				499	
Cyanide			(0)			(0)					
Lead			(0)			(0)				490	
Mercury			(0)			(0)				4	
Nickel			(0)			(0)					
Selenium			(0)			(0)				0	
Silver			(0)			(0)				109	
Thallium			(0)			(0)					
Zinc			(0)			(0)				811	
Pesticides, PCBs, etc.											
Acrolein			(0)			(0)					
Aldrin			(0)			(0)					
Chlorodane			(0)			(0)					
DDD			(0)			(0)					
DDE			(0)			(0)					
DDT			(0)			(0)					

NOTE: [a] = Skagit River, see Table 4-1.

Dieldrin			(0)			(0)				
Endosulfan and Endosulfan Sulfate			(0)			(0)				
Endrin and Endrin Aldehyde			(0)			(0)				
Heptachlor			(0)			(0)				
Heptachlor Epoxide			(0)			(0)				
Hexachlorocyclohexane Isomers			(0)			(0)				
Isophorone			(0)			(0)				
TCDD			(0)			(0)				
Toxaphene			(0)			(0)				
PCBs			(0)			(0)				
2-Chloronaphthalene			(0)			(0)				
Halogenated Aliphatic Hydrocarbons										
Methyl Chloride			(0)			(0)				
Methylene Chloride			(0)			(0)				
Chloroform			(0)			(0)				
Carbon Tetrachloride			(0)			(0)				
Chloroethane			(0)			(0)				
1,1-Dichloroethane			(0)			(0)				
1,2-Dichloroethane			(0)			(0)				
1,1,1-Trichloroethane			(0)			(0)				
1,1,2-Trichloroethane			(0)			(0)				
1,1,2,2-Tetrachloroethane			(0)			(0)				
Hexachloroethane			(0)			(0)				
Vinyl Chloride			(0)			(0)				
1,1-Dichloroethylene			(0)			(0)				
1,2-trans-Dichloroethylene			(0)			(0)				
Trichloroethylene			(0)			(0)				
Tetrachloroethylene			(0)			(0)				
1,2-Dichloropropane			(0)			(0)				
1,3-Dichloropropene			(0)			(0)				
Hexachlorobutadiene			(0)			(0)				
Hexachlorocyclopentadiene			(0)			(0)				
Methyl Bromide			(0)			(0)				
Dichlorobromomethane			(0)			(0)				
Chlorodibromomethane			(0)			(0)				
Bromoform			(0)			(0)				
Dichlorodifluoromethane			(0)			(0)				
Trichlorofluoromethane			(0)			(0)				
Halogenated Ethers										
Bis(chloromethyl) Ether			(0)			(0)				
Bis(2-chloroethyl) Ether			(0)			(0)				

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Bis(2-chloroiso-propyl) Ether			(0)			(0)				
2-chloroethyl Vinyl Ether			(0)			(0)				
4-chlorophenyl Phenyl Ether			(0)			(0)				
4-Bromophenyl Phenyl Ether			(0)			(0)				
Bis(2-chloroethoxy) Methane			(0)			(0)				
Monocyclic Aromatics										
Benzene			(0)			(0)				
Chlorobenzene			(0)			(0)				
1,2-Dichlorobenzene			(0)			(0)				
1,3-Dichlorobenzene			(0)			(0)				
1,4-Dichlorobenzene			(0)			(0)				
1,2,4-Trichloro-benzene			(0)			(0)				
Hexachlorobenzene			(0)			(0)				
Ethylbenzene			(0)			(0)				
Nitrobenzene			(0)			(0)				
Toluene			(0)			(0)				
2,4-Dinitrotoluene			(0)			(0)				
2,6-Dinitrotoluene			(0)			(0)				
Phenol			(0)			(0)				
2-Chlorophenol			(0)			(0)				
2,4-Dichlorophenol			(0)			(0)				
2,4,6-Tricholoro-phenol			(0)			(0)				
Pentachlorophenol			(0)			(0)				
2-Nitrophenol			(0)			(0)				
4-Nitrophenol			(0)			(0)				
2,4-Dinitrophenol			(0)			(0)				
2,4-Dimethyl Phenol			(0)			(0)				
p-Chloro-m-cresol			(0)			(0)				
4,6-Dinitro-o-cresol			(0)			(0)				
Phthalate Esters										
Dimethyl Phthalate			(0)			(0)				
Diethyl Phthalate			(0)			(0)				
Di-n-butyl Phthalate			(0)			(0)				
Di-n-octyl Phthalate			(0)			(0)				
Bis(2-ethylhexyl) Phthalate			(0)			(0)				
Butyl Benzyl Phthalate			(0)			(0)				
Polycyclic Aromatic Hydrocarbons										
Acenaphthene			(0)			(0)				
Acenaphthylene			(0)			(0)				
Fluorene			(0)			(0)				
Napthalene			(0)			(0)				
Anthracene			(0)			(0)				

Fluoranthene			(0)			(0)				
Phenanthrene			(0)			(0)				
Benzo[a]anthracene			(0)			(0)				
Benzo[b]fluoranthene			(0)			(0)				
Benzo[k]fluoranthene			(0)			(0)				
Chrysene			(0)			(0)				
Pyrene			(0)			(0)				
Benzo[ghi]perylene			(0)			(0)				
Benzo[a]pyrene			(0)			(0)				
Dibenzo[a]anthracene			(0)			(0)				
Indeno[1,2,3-cd]-pyrene			(0)			(0)				
Nitrosamines & Misc.										
N-nitrosodimethylamine			(0)			(0)				
N-nitrosodiphenylamine			(0)			(0)				
N-nitrosodi-n-propylamine			(0)			(0)				
Benzidine			(0)			(0)				
3,3'-Dichlorobenzidine			(0)			(0)				
1,2-Diphenylhydrazine			(0)			(0)				
Acrylonitrile			(0)			(0)				

Appendix D. Mass loading values calculated from available data. Number of sources contributing to each calculated value is shown in parentheses. Data for all values are given in kg/day, except where noted.

Receiving Water Port Gardner	Municipal (3) Wet	Municipal (3) Dry	Municipal (3) Annual	Industrial (4) Wet	Industrial (4) Dry	Industrial (4) Annual	Total for NPDES Permitted Dischargers Wet	Total for NPDES Permitted Dischargers Dry	Total for NPDES Permitted Dischargers Annual	Nonpermitted Sources Annual[a]	Grand Total Annual
CONVENTIONAL POLLUTANT											
Flow (cubic m/d)			43,711 (3)	84,657	83,522	84,184 (1)			127,895		
Biochemical Oxygen Demand (BOD)	1,089	1,814	1,391 (3)	5,126	3,720	4,540 (1)	6,215	5,534	5,931		
Total Suspended Solids	1,266	2,236	1,670 (3)	4,763	4,672	4,725 (1)	6,029	6,908	6,395		
Oils & Grease			(0)		422	422 (1)					
pH (range)	6.5-9.2	6.6-10.0	6.5-10.0 (3)	5.9-7.1	6.1-7.0	5.9-7.1 (1)	5.9-9.2	6.1-10.0	5.9-10.0		
Fecal Coliform (MPN/100 ml)	5-2,500	5-2,200	5-2,500 (3)	41,500		41,500 (1)	5-41,500		5-41,500		
EXTENDED CONVENTIONAL POLLUTANT											
Chemical Oxygen Demand (COD)	272		272 (1)	64,685	64,142	64,458 (1)	64,957		64,686		
Total Solids	599		599 (1)	150,465		150,465 (1)	151,064		151,064		
Total Nonvolatile Solids			(0)	82,468		82,468 (1)					
Total Nonvolatile Suspended Solids			(0)	989		989 (1)					
Total Nitrogen	36		36 (1)	2,427	1,445	2,018 (1)	2,463		2,054		
Total Phosphorus	18		18 (1)	308	259	287 (1)	326		305		
PRIORITY POLLUTANT											
Heavy Metals & Inorg.											
Antimony			(0)		0.04	0.04 (1)					
Arsenic			(0)		0.02	0.02 (1)					
Asbestos (fibers/d)			(0)		ND	ND (1)				21	
Beryllium			(0)	0.4	0.1	0.2 (1)			2	41	43
Cadmium		0.8	(2)	1	2	1 (1)			3	34	37
Chromium		0.2	(1)	2	3	3 (1)					
Copper			(0)	ND	ND	ND (1)				31	
Cyanide			(0)	7	3	5 (1)				7	
Lead			(0)	ND	0.01	<0.01 (1)				145	
Mercury			(0)	4	0.6	3 (1)					
Nickel			(0)	ND	0.03	0.01 (1)					
Selenium			(0)	0.02	0.3	0.1 (1)					
Silver			(0)		4	4 (1)			6	744	750
Thallium		0.4	(1)	9	1	6 (1)					
Zinc		0.5									
Pesticides, PCBs, etc.											
Acrolein			(0)		ND	ND (1)					
Aldrin			(0)		ND	ND (1)					
Chlorodane			(0)		ND	ND (1)					
DDD			(0)		ND	ND (1)					
DDE			(0)		ND	ND (1)					
DDT			(0)		ND	ND (1)					

[a] = Snohomish River, see Table 4-1.

Dieldrin			(0)		ND	ND	(1)			
Endosulfan and Endosulfan Sulfate			(0)		ND	ND	(1)			
Endrin and Endrin Aldehyde			(0)		ND	ND	(1)			
Heptachlor			(0)		ND	ND	(1)			
Heptachlor Epoxide			(0)		ND	ND	(1)			
Hexachlorocyclohexane Isomers			(0)		ND	ND	(1)			
Isophorone			(0)		ND	ND	(1)			
TCDD			(0)		ND	ND	(1)			
Toxaphene			(0)		ND	ND	(1)			
PCBs			(0)		ND	ND	(1)			
2-Chloronaphthalene			(0)		ND	ND	(1)			
Halogenated Aliphatic Hydrocarbons										
Methyl Chloride			(0)		ND	ND	(1)			
Methylene Chloride			(0)		0.5	0.5	(1)			
Chloroform			(0)		12	12	(1)			
Carbon Tetrachloride			(0)		ND	ND	(1)			
Chloroethane			(0)		ND	ND	(1)			
1,1-Dichloroethane			(0)		ND	ND	(1)			
1,2-Dichloroethane			(0)		ND	ND	(1)			
1,1,1-Trichloroethane			(0)		ND	ND	(1)			
1,1,2-Trichloroethane			(0)		ND	ND	(1)			
1,1,2,2-Tetrachloroethane			(0)		ND	ND	(1)			
Hexachloroethane			(0)		ND	ND	(1)			
Vinyl Chloride			(0)		ND	ND	(1)			
1,1-Dichloroethylene			(0)		ND	ND	(1)			
1,2-trans-Dichloroethylene			(0)		ND	ND	(1)			
Trichloroethylene			(0)		ND	ND	(1)			
Tetrachloroethylene			(0)		ND	ND	(1)			
1,2-Dichloropropane			(0)		ND	ND	(1)			
1,3-Dichloropropene			(0)		ND	ND	(1)			
Hexachlorobutadiene			(0)		ND	ND	(1)			
Hexachlorocyclopentadiene			(0)		ND	ND	(1)			
Methyl Bromide			(0)		ND	ND	(1)			
Dichlorobromomethane			(0)		ND	ND	(1)			
Chlorodibromomethane			(0)		ND	ND	(1)			
Bromoform			(0)		ND	ND	(1)			
Dichlorodifluoromethane			(0)		ND	ND	(1)			
Trichlorofluoromethane			(0)		ND	ND	(1)			
Halogenated Ethers										
Bis(chloromethyl) Ether			(0)		ND	ND	(1)			
Bis(2-chloroethyl) Ether			(0)		ND	ND	(1)			

Bis(2-chloroiso-propyl) Ether			(0)	ND	ND	(1)				
2-chloroethyl Vinyl Ether			(0)	ND	ND	(1)				
4-chlorophenyl Phenyl Ether			(0)	ND	ND	(1)				
4-Bromophenyl Phenyl Ether			(0)	ND	ND	(1)				
Bis(2-chloroethoxy) Methane			(0)	ND	ND	(1)				
Monocyclic Aromatics										
Benzene			(0)	ND	ND	(1)				
Chlorobenzene			(0)	ND	ND	(1)				
1,2-Dichlorobenzene			(0)	ND	ND	(1)				
1,3-Dichlorobenzene			(0)	ND	ND	(1)				
1,4-Dichlorobenzene			(0)	ND	ND	(1)				
1,2,4-Trichloro-benzene			(0)	ND	ND	(1)				
Hexachlorobenzene			(0)	4	4	(1)				
Ethylbenzene			(0)	ND	ND	(1)				
Nitrobenzene			(0)	ND	ND	(1)				
Toluene			(0)	ND	ND	(1)				
2,4-Dinitrotoluene			(0)	ND	ND	(1)				
2,6-Dinitrotoluene			(0)	ND	ND	(1)				
Phenol			(0)	ND	ND	(1)				
2-Chlorophenol			(0)	ND	ND	(1)				
2,4-Dichlorophenol			(0)	ND	ND	(1)				
2,4,6-Tricholoro-phenol			(0)	0.2	0.2	(1)				
Pentachlorophenol			(0)	ND	ND	(1)				
2-Nitrophenol			(0)	ND	ND	(1)				
4-Nitrophenol			(0)	ND	ND	(1)				
2,4-Dinitrophenol			(0)	ND	ND	(1)				
2,4-Dimethyl Phenol			(0)	ND	ND	(1)				
p-Chloro-m-cresol			(0)	ND	ND	(1)				
4,6-Dinitro-o-cresol			(0)	ND	ND	(1)				
Phthalate Esters										
Dimethyl Phthalate			(0)	ND	ND	(1)				
Diethyl Phthalate			(0)	ND	ND	(1)				
Di-n-butyl Phthalate			(0)	ND	ND	(1)				
Di-n-octyl Phthalate			(0)	ND	ND	(1)				
Bis(2-ethylhexyl) Phthalate			(0)	0.5	0.5	(1)				
Butyl Benzyl Phthalate			(0)	0.5	0.5	(1)				
Polycyclic Aromatic Hydrocarbons										
Acenaphthene			(0)	ND	ND	(1)				
Acenaphthylene			(0)	ND	ND	(1)				
Fluorene			(0)	ND	ND	(1)				
Napthalene			(0)	ND	ND	(1)				
Anthracene			(0)	ND	ND	(1)				

Appendix D. Mass loading values calculated from available data. Number of sources contributing to each calculated value is shown in parentheses. Data for all values are given in kg/day, except where noted.

Receiving Water Central Basin	Municipal (25) Wet	Municipal (25) Dry	Municipal (25) Annual	Industrial (15) Wet	Industrial (15) Dry	Industrial (15) Annual	Total for NPDES Permitted Dischargers Wet	Total for NPDES Permitted Dischargers Dry	Total for NPDES Permitted Dischargers Annual	Nonpermitted Sources Annual	Grand Total Annual
CONVENTIONAL POLLUTANT											
Flow (cubic m/d)	734,644	505,065	638,986 (22)	103,020	92,755	98,740 (9)	837,778	597,820	737,060		
Biochemical Oxygen Demand (BOD)	55,364	58,258	56,570 (20)	786	655	732 (4)	56,150	58,913	57,326		
Total Suspended Solids	43,378	56,965	49,039 (2)	2,703	2,210	2,497 (5)	46,082	59,176	51,555		
Oils & Grease			39 (0)			376 (4)					
pH (range)	5.7-9.1	5.9-8.0	5.7-9.1 (22)	5.5-7.2	6.5-7.8	6.5-7.8 (8)	5.7-9.1	5.9-8.0	5.7-9.1		
Fecal Coliform (MPN/100 ml)	0-790	10-4,850	0-4,850 (22)	9	0-48	0-48 (4)	0-790	0-4,850	0-4,850		
EXTENDED CONVENTIONAL POLLUTANT											
Chemical Oxygen Demand (COD)			3,089 (3)	25,038		25,038 (1)			28,213		
Total Solids			3,606 (2)	316,920		316,920 (1)			320,526		
Total Nonvolatile Solids			1,597 (2)	273,350		273,350 (1)			274,947		
Total Nonvolatile Suspended Solids			18 (2)	55		55 (1)			73		
Total Nitrogen			185 (2)	297		297 (2)			482		
Total Phosphorus			84 (2)	49		49 (1)			133		
PRIORITY POLLUTANT											
Heavy Metals & Inorg.											
Antimony	94	5	57 (4)	0.6		0.6 (1)	95		58		
Arsenic	144	6	86 (2)	0.8		0.8 (1)	145		87		
Asbestos (fibers/d)	3×10^{17}	2×10^{17}	3×10^{17} (4)			(0)					
Beryllium	2	1	2 (4)	0.8		0.8 (1)	3		3		
Cadmium	4	2	3 (5)	0.6		0.6 (2)	5		4		
Chromium	18	18	18 (5)	0.6		0.6 (2)	18		19		
Copper	88	62	77 (5)	1		1 (2)	89		78	5	82
Cyanide	42	7	27 (4)	0.3		0.3 (2)	42		27		
Lead	56	21	41 (5)	2		2 (1)	58		43	5	48
Mercury	0.2	0.4	0.3 (4)	0.02		0.02 (2)	.2		0.3		
Nickel	21	22	21 (5)	0.6		0.6 (2)	22		22	3	25
Selenium	0.6	0.4	0.5 (2)	0.6		0.6 (1)	1		1		
Silver	12	3	8 (2)	0.5		0.5 (1)	12		8		
Thallium	0.6	2	1 (2)	0.7		0.7 (1)	1		2		
Zinc	153	88	126 (5)	2		2 (2)	155		128	14	142
Pesticides, PCBs, etc.											
Acrolein	ND	ND	ND (4)	ND		ND (1)	ND		ND		
Aldrin	ND	ND	ND (4)	ND		ND (1)	ND		ND		
Chlorodane	ND	<0.01	<0.01 (4)	ND		ND (1)	ND		<0.01		
DDD	ND	ND	ND (4)	ND		ND (1)	ND		ND		
DDE	ND		ND (4)	ND		ND (1)	ND		ND		
DDT	ND		ND (4)	ND		ND (1)	ND		ND		

NOTE: [a] = Lake Washington Ship Canal, see Table 4-1.

Fluoranthene			(0)		ND	ND	(1)			
Phenanthrene			(0)		ND	ND	(1)			
Benzo[a]anthracene			(0)		ND	ND	(1)			
Benzo[b]fluoranthene			(0)		ND	ND	(1)			
Benzo[k]fluoranthene			(0)		ND	ND	(1)			
Chrysene			(0)		ND	ND	(1)			
Pyrene			(0)		ND	ND	(1)			
Benzo[ghi]perylene			(0)		ND	ND	(1)			
Benzo[a]pyrene			(0)		ND	ND	(1)			
Dibenzo[a]anthracene			(0)		ND	ND	(1)			
Indeno[1,2,3-cd]-pyrene			(0)		ND	ND	(1)			
Nitrosamines & Misc.										
N-nitrosodimethylamine			(0)		ND	ND	(1)			
N-nitrosodiphenylamine			(0)		ND	ND	(1)			
N-nitrosodi-n-propylamine			(0)		ND	ND	(1)			
Benzidine			(0)		ND	ND	(1)			
3,3'-Dichlorobenzidine			(0)		ND	ND	(1)			
1,2-Diphenylhydrazine			(0)		ND	ND	(1)			
Acrylonitrile			(0)		ND	ND	(1)			

Dieldrin	ND		ND (4)	ND		ND (1)	ND	ND
Endosulfan and Endosulfan Sulfate	ND	ND	ND (4)	ND		ND (1)	ND	ND
Endrin and Endrin Aldehyde	ND	ND	ND (4)	ND		ND (1)	ND	ND
Heptachlor	ND	ND	ND (4)	ND		ND (1)	ND	ND
Heptachlor Epoxide	ND	ND	ND (4)	ND		ND (1)	ND	ND
Hexachlorocyclohexane Isomers	ND	0.04	0.01 (4)	ND		ND (1)	ND	0.01
Isophorone	ND	4	2 (4)	ND		ND (1)	ND	2
TCDD	ND	0.4	0.2 (4)	ND		ND (1)	ND	0.2
Toxaphene	ND	0.4	0.2 (4)	ND		ND (1)	ND	0.2
PCBs	ND	<0.01	<0.01 (4)	ND		ND (1)	ND	<0.01
2-Chloronaphthalene	ND	ND	ND (4)	ND		ND (1)	ND	ND
Halogenated Aliphatic Hydrocarbons								
Methyl Chloride	0.3	1	0.6 (4)	ND		ND (1)	0.3	0.6
Methylene Chloride	23	24	24 (4)	ND		ND (1)	23	24
Chloroform	11	3	8 (4)	ND		ND (1)	11	8
Carbon Tetrachloride	ND	ND	ND (4)	ND		ND (1)	ND	ND
Chloroethane	ND	ND	ND (4)	ND		ND (1)	ND	ND
1,1-Dichloroethane	0.03	ND	0.02 (4)	ND		ND (1)	0.03	0.02
1,2-Dichloroethane	ND	ND	ND (4)	ND		ND (1)	ND	ND
1,1,1-Trichloroethane	2	ND	ND (4)	ND		ND (1)	2	1
1,1,2-Trichloroethane	ND	ND	ND (4)	ND		ND (1)	ND	ND
1,1,2,2-Tetrachloroethane	ND	ND	ND (4)	ND		ND (1)	ND	ND
Hexachloroethane	ND	ND	ND (4)	ND		ND (1)	ND	ND
Vinyl Chloride	ND	ND	ND (4)	ND		ND (1)	ND	ND
1,1-Dichloroethylene	24	15	20 (4)	ND		ND (1)	24	20
1,2-trans-Dichloroethylene	10	4	8 (4)	ND		ND (1)	10	8
Trichloroethylene	18	1	11 (4)	ND		ND (1)	18	11
Tetrachloroethylene	10	2	6 (4)	ND		ND (1)	10	6
1,2-Dichloropropane	0.01	ND	0.01 (4)	ND		ND (1)	0.01	0.01
1,3-Dichloropropene	ND	ND	ND (4)	ND		ND (1)	ND	ND
Hexachlorobutadiene	ND	ND	ND (4)	ND		ND (1)	ND	ND
Hexachlorocyclopentadiene	ND	0.4	0.2 (4)	ND		ND (1)	ND	0.2
Methyl Bromide	0.5	1	0.9 (4)	ND		ND (1)	0.5	0.9
Dichlorobromomethane	ND	ND	ND (4)	ND		ND (1)	ND	ND
Chlorodibromomethane	ND	ND	ND (4)	ND		ND (1)	ND	ND
Bromoform	ND	ND	ND (4)	ND		ND (1)	ND	ND
Dichlorodifluoromethane	ND	ND	ND (4)	ND		ND (1)	ND	ND
Trichlorofluoromethane	0.01	0.7	0.3 (4)	ND		ND (1)	0.01	0.3
Halogenated Ethers								
Bis(chloromethyl) Ether	ND	ND	ND (4)	ND		ND (1)	ND	ND
Bis(2-chloroethyl) Ether	ND	ND	ND (4)	ND		ND (1)	ND	ND

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Bis(2-chloroiso-propyl) Ether	ND	T	T (4)	ND	ND (1)	ND	T	
2-chloroethyl Vinyl Ether	ND	ND	ND (4)	ND	ND (1)	ND	ND	
4-chlorophenyl Phenyl Ether	ND	ND	ND (4)	ND	ND (1)	ND	ND	
4-Bromophenyl Phenyl Ether	ND	ND	ND (4)	ND	ND (1)	ND	ND	
Bis(2-chloroethoxy) Methane	ND	T	T (4)	ND	ND (1)	ND	T	
Monocyclic Aromatics								
Benzene	26	2	16 (4)	ND	ND (1)	26	16	
Chlorobenzene	ND	0.7	0.3 (4)	ND	ND (1)	ND	0.3	
1,2-Dichlorobenzene	ND	1	0.5 (4)	ND	ND (1)	ND	0.5	
1,3-Dichlorobenzene	ND	0.04	0.01 (4)	ND	ND (1)	ND	0.01	
1,4-Dichlorobenzene	ND	2	0.9 (4)	ND	ND (1)	ND	0.9	
1,2,4-Trichloro-benzene	ND	ND	ND (4)	ND	ND (1)	ND	ND	
Hexachlorobenzene	ND	ND	ND (4)	ND	ND (1)	ND	ND	
Ethylbenzene	23	1	14 (4)	ND	ND (1)	24	14	
Nitrobenzene	ND	T	T (4)	ND	ND (1)	ND	T	
Toluene	69	45	59 (4)	ND	ND (1)	69	59	
2,4-Dinitrotoluene	ND	ND	ND (4)	ND	ND (1)	ND	ND	
2,6-Dinitrotoluene	ND	ND	ND (4)	ND	ND (1)	ND	ND	
Phenol	10	3	7 (4)	ND	ND (1)	10	7	
2-Chlorophenol	ND	ND	ND (4)	ND	ND (1)	ND	ND	
2,4-Dichlorophenol	ND	ND	ND (4)	ND	ND (1)	ND	ND	
2,4,6-Tricholoro-phenol	ND	0.2	0.08 (4)	ND	ND (1)	ND	0.08	
Pentachlorophenol	3	5	4 (4)	ND	ND (1)	3	4	
2-Nitrophenol	ND	ND	ND (4)	ND	ND (1)	ND	ND	
4-Nitrophenol	ND	ND	ND (4)	ND	ND (1)	ND	ND	
2,4-Dinitrophenol	ND	ND	ND (4)	ND	ND (1)	ND	ND	
2,4-Dimethyl Phenol	ND	0.07	0.03 (4)	ND	ND (1)	ND	0.03	
p-Chloro-m-cresol		ND	ND (1)	ND	ND (1)	ND	ND	
4,6-Dinitro-o-cresol	ND	ND	ND (4)	ND	ND (1)	ND	ND	
Phthalate Esters								
Dimethyl Phthalate	ND	T	T (4)	ND	ND (1)	ND	T	
Diethyl Phthalate	0.6	3	2 (4)	2	2 (1)	3	4	
Di-n-butyl Phthalate	3	0.9	2 (4)	ND	ND (1)	3	2	
Di-n-octyl Phthalate	ND	ND	ND (4)	ND	ND (1)	ND	ND	
Bis(2-ethylhexyl) Phthalate	9	14	11 (4)	ND	ND (1)	9	11	
Butyl Benzyl Phthalate	ND	0.2	0.09 (4)	ND	ND (1)	ND	0.09	
Polycyclic Aromatic Hydrocarbons								
Acenaphthene	ND	ND	ND (4)	ND	ND (1)	ND	ND	
Acenaphthylene	ND	ND	ND (4)	ND	ND (1)	ND	ND	
Fluorene	ND	ND	ND (4)	ND	ND (1)	ND	ND	
Napthalene	21	4	14 (4)	ND	ND (1)	21	14	
Anthracene	ND	ND	ND (4)	ND	ND (1)	ND	ND	

3

Fluoranthene	ND	0.2	0.06 (4)	ND		ND (1)	ND	0.06
Phenanthrene	ND	ND	ND (4)	ND		ND (1)	ND	ND
Benzo[a]anthracene	ND	ND	ND (4)	ND		ND (1)	ND	ND
Benzo[b]fluoranthene	ND	ND	ND (4)	ND		ND (1)	ND	ND
Benzo[k]fluoranthene	ND	ND	ND (4)	ND		ND (1)	ND	ND
Chrysene	ND	ND	ND (4)	ND		ND (1)	ND	ND
Pyrene	ND	ND	ND (4)	ND		ND (1)	ND	ND
Benzo[ghi]perylene	ND	ND	ND (4)	ND		ND (1)	ND	ND
Benzo[a]pyrene	ND	ND	ND (4)	ND		ND (1)	ND	ND
Dibenzo[a]anthracene	ND	ND	ND (4)	ND		ND (1)	ND	ND
Indeno[1,2,3-cd]-pyrene	ND	ND	ND (4)	ND		ND (1)	ND	ND
Nitrosamines & Misc.								
N-nitrosodimethylamine	ND	ND	ND (4)	ND		ND (1)	ND	ND
N-nitrosodiphenylamine	ND	ND	ND (4)	ND		ND (1)	ND	ND
N-nitrosodi-n-propylamine	ND	ND	ND (4)	ND		ND (1)	ND	ND
Benzidine	ND	0.4	0.2 (4)	ND		ND (1)	ND	0.2
3,3'-Dichlorobenzidine	ND	ND	ND (4)	ND		ND (1)	ND	ND
1,2-Diphenylhydrazine	ND	ND	ND (4)	ND		ND (1)	ND	ND
Acrylonitrile	ND	ND	ND (4)	ND		ND (1)	ND	ND

Appendix D. Mass loading values calculated from available data. Number of sources contributing to each calculated value is shown in parentheses. Data for all values are given in kg/day, except where noted.

Receiving Water	Municipal (0)			Industrial (29)			Total for NPDES Permitted Dischargers			Nonpermitted Sources	Grand Total
Elliott Bay	Wet	Dry	Annual	Wet	Dry	Annual	Wet	Dry	Annual	Annual[a]	Annual
CONVENTIONAL POLLUTANT											
Flow (cubic m/d)				7,295	7,750	7,485 (15)	7,295	7,750	7,485	5×10^{6}[b]	5×10^{6}
Biochemical Oxygen Demand (BOD)						(0)					
Total Suspended Solids				62	108	81 (2)	62	108	81		
Oils & Grease				26	25	26 (7)	26	25	26	795[b]	821
pH (range)				5.0-8.0	5.0-12.7	5.0-12.7 (9)	5.0-8.0	5.0-12.7	5.0-12.7		
Fecal Coliform (MPN/100 ml)						(0)				7×10^{12}[b]	
EXTENDED CONVENTIONAL POLLUTANT											
Chemical Oxygen Demand (COD)						(0)					
Total Solids						(0)					
Total Nonvolatile Solids						(0)					
Total Nonvolatile Suspended Solids						(0)					
Total Nitrogen						(0)					
Total Phosphorus						(0)					
PRIORITY POLLUTANT											
Heavy Metals & Inorg.											
Antimony						(0)					
Arsenic						(0)				11[b]	
Asbestos (fibers/d)						(0)					
Beryllium						(0)					
Cadmium					<0.01	<0.01 (1)		<0.01	<0.01	17	17[b]
Chromium				16	19	17 (2)	16	19	17	6	23
Copper						2 (3)			2	29	31
Cyanide						(0)					
Lead					<0.01	<0.01 (1)		<0.01	<0.01	5	5
Mercury						(0)				.4[b]	
Nickel					<0.01	<0.01 (1)		<0.01	<0.01	35	35
Selenium						(0)					
Silver				0.05		0.05 (1)	0.05		0.05		
Thallium						(0)					
Zinc				0.3	0.4	0.3 (4)	0.3	0.4	0.3	135	135
Pesticides, PCBs, etc.											
Acrolein						(0)					
Aldrin						(0)					
Chlorodane						(0)					
DDD						(0)					
DDE						(0)					
DDT						(0)					

NOTE: [a] = Duwamish River, see Table 4-1. [b] = Duwamish River data from Harper-Owes 1983, taken near mouth.

[illegible]						(0)				
[illegible] and Endosulfan Sulfate						(0)				
Endrin and Endrin Aldehyde						(0)				
Heptachlor						(0)				
Heptachlor Epoxide						(0)				
Hexachlorocyclohexane Isomers						(0)				
Isophorone						(0)				
PCBs						(0)				0.1[b]
Toxaphene						(0)				
2-Chloronaphthalene						(0)				
Halogenated Aliphatic Hydrocarbons										
Methyl Chloride						(0)				
Methylene Chloride						(0)				
Chloroform						(0)				
Carbon Tetrachloride						(0)				
Chloroethane						(0)				
1,1-Dichloroethane						(0)				
1,2-Dichloroethane						(0)				
1,1,1-Trichloroethane						(0)				
1,1,2-Trichloroethane						(0)				
1,1,2,2-Tetrachloroethane						(0)				
Hexachloroethane						(0)				
Vinyl Chloride						(0)				
1,1-Dichloroethylene						(0)				
1,2-trans-Dichloroethylene						(0)				
Trichloroethylene						(0)				
Tetrachloroethylene						(0)				
1,2-Dichloropropane						(0)				
1,3-Dichloropropene						(0)				
Hexachlorobutadiene						(0)				
Hexachlorocyclopentadiene						(0)				
Methyl Bromide						(0)				
Dichlorobromomethane						(0)				
Chlorodibromomethane						(0)				
Bromoform						(0)				
Dichlorodifluoromethane						(0)				
Trichlorofluoromethane						(0)				
Halogenated Ethers										
Bis(chloromethyl) Ether						(0)				
Bis(2-chloroethyl) Ether						(0)				

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Bis(2-chloroiso-propyl) Ether						(0)				
2-chloroethyl Vinyl Ether						(0)				
4-chlorophenyl Phenyl Ether						(0)				
4-Bromophenyl Phenyl Ether						(0)				
Bis(2-chloroethoxy) Methane						(0)				
Monocyclic Aromatics										
Benzene						(0)				
Chlorobenzene						(0)				
1,2-Dichlorobenzene						(0)				
1,3-Dichlorobenzene						(0)				
1,4-Dichlorobenzene						(0)				
1,2,4-Trichloro-benzene						(0)				
Hexachlorobenzene						(0)				
Ethylbenzene						(0)				
Nitrobenzene						(0)				
Toluene						(0)				
2,4-Dinitrotoluene						(0)				
2,6-Dinitrotoluene						(0)				
Phenol						(0)				
2-Chlorophenol						(0)				
2,4-Dichlorophenol						(0)				
2,4,6-Tricholoro-phenol						(0)				
Pentachlorophenol						(0)				
2-Nitrophenol						(0)				
4-Nitrophenol						(0)				
2,4-Dinitrophenol						(0)				
2,4-Dimethyl Phenol						(0)				
p-Chloro-m-cresol						(0)				
4,6-Dinitro-o-cresol						(0)				
Phthalate Esters										
Dimethyl Phthalate						(0)				
Diethyl Phthalate						(0)				
Di-n-butyl Phthalate						(0)				
Di-n-octyl Phthalate						(0)				
Bis(2-ethylhexyl) Phthalate						(0)				
Butyl Benzyl Phthalate						(0)				
Polycyclic Aromatic Hydrocarbons										
Acenaphthene						(0)				
Acenaphthylene						(0)				
Fluorene						(0)				
Napthalene						(0)				9^b
Anthracene						(0)				

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Fluoranthene						(0)			
Phenanthrene						(0)			
Benzo[a]anthracene						(0)			
Benzo[b]fluoranthene						(0)			
Benzo[k]fluoranthene						(0)			
Chrysene						(0)			
Pyrene						(0)			
Benzo[ghi]perylene						(0)			
Benzo[a]pyrene						(0)			
Dibenzo[a]anthracene						(0)			
Indeno[1,2,3-cd]-pyrene						(0)			
Nitrosamines & Misc.									
N-nitrosodimethylamine						(0)			
N-nitrosodiphenylamine						(0)			
N-nitrosodi-n-propylamine						(0)			
Benzidine						(0)			
3,3'-Dichlorobenzidine						(0)			
1,2-Diphenylhydrazine						(0)			
Acrylonitrile						(0)			

Appendix D. Mass loading values calculated from available data. Number of sources contributing to each calculated value is shown in parentheses. Data for all values are given in kg/day, except where noted.

Receiving Water	Municipal (_4_) Wet	Municipal (_4_) Dry	Municipal (_4_) Annual	Industrial (_1_) Wet	Industrial (_1_) Dry	Industrial (_1_) Annual	Total for NPDES Permitted Dischargers Wet	Total for NPDES Permitted Dischargers Dry	Total for NPDES Permitted Dischargers Annual	Nonpermitted Sources Annual	Grand Total Annual
Sinclair Inlet											
CONVENTIONAL POLLUTANT											
Flow (cubic m/d)	27,037	16,894	22,810		24,090	24,090 (1)		40,984	46,900		
Biochemical Oxygen Demand (BOD)	2,694	2,041	2,422 (4)			(0)					
Total Suspended Solids	1,964	1,397	1,729 (4)			(0)					
Oils & Grease			(0)		13	13 (1)					
pH (range)	6.2-9.4	6.5-9.3	6.2-9.4 (4)		7.6-7.7	7.5-7.7 (1)		6.5-9.3	6.2-9.4		
Fecal Coliform (MPN/100 ml)	10-238	9-176	9-238 (4)			(0)					
EXTENDED CONVENTIONAL POLLUTANT											
Chemical Oxygen Demand (COD)			7,984 (4)			(0)					
Total Solids			20,186 (4)			(0)					
Total Nonvolatile Solids			15,786 (4)			(0)					
Total Nonvolatile Suspended Solids			259 (4)			(0)					
Total Nitrogen			468 (4)			(0)					
Total Phosphorus			209 (4)			(0)					
PRIORITY POLLUTANT											
Heavy Metals & Inorg.						(0)					
Antimony			(0)			(0)					
Arsenic			(0)			(0)					
Asbestos (fibers/d)			(0)			(0)					
Beryllium			(0)			(0)					
Cadmium	0.1		0.1 (1)			(0)					
Chromium	0.7		0.7 (1)			(0)					
Copper	2		2 (1)			(0)					
Cyanide	0.2		0.2 (1)			(0)					
Lead	1		1 (1)			(0)					
Mercury			(0)			(0)					
Nickel	0.5		0.5 (1)			(0)					
Selenium			(0)			(0)					
Silver			(0)			(0)					
Thallium			(0)			(0)					
Zinc	3		3 (1)			(0)					
Pesticides, PCBs, etc.											
Acrolein			(0)			(0)					
Aldrin			(0)			(0)					
Chlorodane			(0)			(0)					
DDD			(0)			(0)					
DDE			(0)			(0)					
DDT			(0)			(0)					

Dieldrin			(0)			(0)				
Endosulfan and Endosulfan Sulfate			(0)			(0)				
Endrin and Endrin Aldehyde			(0)			(0)				
Heptachlor			(0)			(0)				
Heptachlor Epoxide			(0)			(0)				
Hexachlorocyclohexane Isomers			(0)			(0)				
Isophorone			(0)			(0)				
TCDD			(0)			(0)				
Toxaphene			(0)			(0)				
PCBs			(0)			(0)				
2-Chloronaphthalene			(0)			(0)				
Halogenated Aliphatic Hydrocarbons										
Methyl Chloride			(0)			(0)				
Methylene Chloride			(0)			(0)				
Chloroform			(0)			(0)				
Carbon Tetrachloride			(0)			(0)				
Chloroethane			(0)			(0)				
1,1-Dichloroethane			(0)			(0)				
1,2-Dichloroethane			(0)			(0)				
1,1,1-Trichloroethane			(0)			(0)				
1,1,2-Trichloroethane			(0)			(0)				
1,1,2,2-Tetrachloroethane			(0)			(0)				
Hexachloroethane			(0)			(0)				
Vinyl Chloride			(0)			(0)				
1,1-Dichloroethylene			(0)			(0)				
1,2-trans-Dichloroethylene			(0)			(0)				
Trichloroethylene			(0)			(0)				
Tetrachloroethylene			(0)			(0)				
1,2-Dichloropropane			(0)			(0)				
1,3-Dichloropropene			(0)			(0)				
Hexachlorobutadiene			(0)			(0)				
Hexachlorocyclopentadiene			(0)			(0)				
Methyl Bromide			(0)			(0)				
Dichlorobromomethane			(0)			(0)				
Chlorodibromomethane			(0)			(0)				
Bromoform			(0)			(0)				
Dichlorodifluoromethane			(0)			(0)				
Trichlorofluoromethane			(0)			(0)				
Halogenated Ethers										
Bis(chloromethyl) Ether			(0)			(0)				
Bis(2-chloroethyl) Ether			(0)			(0)				

2

Bis(2-chloroiso-propyl) Ether			(0)			(0)					
2-chloroethyl Vinyl Ether			(0)			(0)					
4-chlorophenyl Phenyl Ether			(0)			(0)					
4-Bromophenyl Phenyl Ether			(0)			(0)					
Bis(2-chloroethoxy) Methane			(0)			(0)					
Monocyclic Aromatics											
Benzene			(0)			(0)					
Chlorobenzene			(0)			(0)					
1,2-Dichlorobenzene			(0)			(0)					
1,3-Dichlorobenzene			(0)			(0)					
1,4-Dichlorobenzene			(0)			(0)					
1,2,4-Trichloro-benzene			(0)			(0)					
Hexachlorobenzene			(0)			(0)					
Ethylbenzene			(0)			(0)					
Nitrobenzene			(0)			(0)					
Toluene			(0)			(0)					
2,4-Dinitrotoluene			(0)			(0)					
2,6-Dinitrotoluene			(0)			(0)					
Phenol			(0)			(0)					
2-Chlorophenol			(0)			(0)					
2,4-Dichlorophenol			(0)			(0)					
2,4,6-Tricholoro-phenol			(0)			(0)					
Pentachlorophenol			(0)			(0)					
2-Nitrophenol			(0)			(0)					
4-Nitrophenol			(0)			(0)					
2,4-Dinitrophenol			(0)			(0)					
2,4-Dimethyl Phenol			(0)			(0)					
p-Chloro-m-cresol			(0)			(0)					
4,6-Dinitro-o-cresol			(0)			(0)					
Phthalate Esters											
Dimethyl Phthalate			(0)			(0)					
Diethyl Phthalate			(0)			(0)					
Di-n-butyl Phthalate			(0)			(0)					
Di-n-octyl Phthalate			(0)			(0)					
Bis(2-ethylhexyl) Phthalate			(0)			(0)					
Butyl Benzyl Phthalate			(0)			(0)					
Polycyclic Aromatic Hydrocarbons											
Acenaphthene			(0)			(0)					
Acenaphthylene			(0)			(0)					
Fluorene			(0)			(0)					
Naphthalene			(0)			(0)					
Anthracene			(0)			(0)					

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Fluoranthene			(0)			(0)				
Phenanthrene			(0)			(0)				
Benzo[a]anthracene			(0)			(0)				
Benzo[b]fluoranthene			(0)			(0)				
Benzo[k]fluoranthene			(0)			(0)				
Chrysene			(0)			(0)				
Pyrene			(0)			(0)				
Benzo[ghi]perylene			(0)			(0)				
Benzo[a]pyrene			(0)			(0)				
Dibenzo[a]anthracene			(0)			(0)				
Indeno[1,2,3-cd]-pyrene			(0)			(0)				
Nitrosamines & Misc.										
N-nitrosodimethylamine			(0)			(0)				
N-nitrosodiphenylamine			(0)			(0)				
N-nitrosodi-n-propylamine			(0)			(0)				
Benzidine			(0)			(0)				
3,3'-Dichlorobenzidine			(0)			(0)				
1,2-Diphenylhydrazine			(0)			(0)				
Acrylonitrile			(0)			(0)				

Appendix D. Mass loading values calculated from available data. Number of sources contributing to each calculated value is shown in parentheses. Data for all values are given in kg/day, except where noted.

Receiving Water Commencement Bay	Municipal (2) Wet	Municipal (2) Dry	Municipal (2) Annual	Industrial (29) Wet	Industrial (29) Dry	Industrial (29) Annual	Total for NPDES Permitted Dischargers Wet	Total for NPDES Permitted Dischargers Dry	Total for NPDES Permitted Dischargers Annual	Nonpermitted Sources Annual[a]	Grand Total Annual
CONVENTIONAL POLLUTANT											
Flow (cubic m/d)	137,120	85,230	115,500 (2)	522,788	548,134	533,349	689,908	633,364	648,523		
Biochemical Oxygen Demand (BOD)	21,080	9,820	16,388 (2)	2,116	4,272	3,016 (4)	23,196	14,092	19,404		
Total Suspended Solids	10,450	6,700	8,890 (2)	4,212	6,338	5,098 (9)	14,662	13,038	13,988		
Oils & Grease	ND	1,630	680 (1)	166	167	166 (7)	166	1,797	846		
pH (range)	6.7-9.1	6.2-7.4	6.2-9.1 (2)	1.4-13.1	0.6-12.6	0.6-13.1 (9)	1.4-13.1	0.6-12.6	0.6-13.1		
Fecal Coliform (MPN/100 ml)	19-455	36-156	19-455 (2)			(0)					
EXTENDED CONVENTIONAL POLLUTANT											
Chemical Oxygen Demand (COD)	54,890	36,200	47,100 (1)		61,346	61,346 (3)		97,546	108,446		
Total Solids	115,220	57,110	91,000 (1)		256,742	(4)		347,742			
Total Nonvolatile Solids	68,500	38,060	55,800 (1)		187,031	(4)		242,831			
Total Nonvolatile Suspended Solids	5,440	2,130	4,060 (1)			1,696 (5)			5,756		
Total Nitrogen	1,950	1,360	1,700 (1)			921 (5)			2,314		
Total Phosphorus	725	570	660 (1)			529 (4)			1,189		
PRIORITY POLLUTANT											
Heavy Metals & Inorg.											
Antimony			(0)			64 (3)					
Arsenic	7	2	5 (2)			34 (6)			39	16	55
Asbestos (fibers/d)		6.9×10^{14}	6.9×10^{14} (2)			(0)					
Beryllium			(0)			2 (1)					
Cadmium	0.6	0.5	0.6 (2)			3 (7)			3	8	11
Chromium	5	5	5 (2)			10 (7)			15	58	143
Copper	15	4	11 (2)			22 (7)			33	66	99
Cyanide	23	1	14 (1)			33 (4)			47	65[c]	112
Lead	24	5	16 (2)			16 (7)			32	91	123
Mercury	0.1	0.06	0.1 (2)			0.02 (6)			0.1	0.7	0.8
Nickel	47	4	29 (2)			24 (7)			53	12	65
Selenium	3	5	4 (2)			5 (2)			9	0	9
Silver	1	1	1 (2)			3 (3)			4	0	4
Thallium			(0)			61 (2)					
Zinc	44	28	37 (2)			39 (7)			76	173	249
Pesticides, PCBs, etc.											
Acrolein			(0)			0.05 (2)					
Aldrin			(0)			ND (2)					
Chlorodane			(0)			ND (1)					
DDD	ND	ND	ND (1)			T[b] (2)			T[b]		
DDE			(0)			T[b] (2)					
DDT	ND	ND	ND (1)			T[b] (2)			T[b]		

[a] = Puyallup River, see Table 4-1 [b] = Present, but also found in blanks [c] = DOE data taken above Cleveland Avenue

Dieldrin				(0)			ND (1)			
Endosulfan and Endosulfan Sulfate				(0)			ND (1)			
Endrin and Endrin Aldehyde				(0)			ND (1)			
Heptachlor				(0)			ND (1)			
Heptachlor Epoxide				(0)			ND (1)			
Hexachlorocyclohexane Isomers	0.3	0.03	0.2	(2)			T (2)		0.2	
Isophorone				(0)			0.02 (2)			
TCDD				(0)			ND (2)			
Toxaphene				(0)			ND (1)			
PCBs	ND	ND	ND	(1)			ND (1)		ND	
2-Chloronaphthalene				(0)			ND (1)			
Halogenated Aliphatic Hydrocarbons										
Methyl Chloride				(0)			0.1 (2)			
Methylene Chloride				(0)			1 (5)			
Chloroform	1	2	1	(0)			220 (7)		221	
Carbon Tetrachloride				(0)			0.02 (5)			
Chloroethane	ND	ND	ND	(1)			T (2)		T	
1,1-Dichloroethane	0.1	ND	0.04	(1)			<0.01 (3)		<0.05	
1,2-Dichloroethane				(0)			0.01 (2)			
1,1,1-Trichloroethane	0.1	0.3	0.2	(1)			0.02 (5)		0.2	
1,1,2-Trichloroethane				(0)			0.01 (2)			
1,1,2,2-Tetrachloroethane	ND	ND	ND	(1)			0.01 (2)		0.01	
Hexachloroethane				(0)			<0.01 (3)			
Vinyl Chloride				(0)			0.01 (2)			
1,1-Dichloroethylene				(0)			0.01 (3)			
1,2-trans-Dichloroethylene	ND	ND	ND	(1)			0.1 (4)		0.1	
Trichloroethylene	0.6	ND	0.4	(1)			0.1 (5)		0.5	
Tetrachloroethylene	0.2	30	13	(1)			0.4 (5)		13	
1,2-Dichloropropane				(0)			0.01 (2)			
1,3-Dichloropropene				(0)			0.01 (2)			
Hexachlorobutadiene	ND	0.1	0.04	(1)			<0.01 (5)		<0.05	
Hexachlorocyclopentadiene				(0)			0.06 (2)			
Methyl Bromide				(0)			0.01 (2)			
Dichlorobromomethane	ND	ND	ND	(1)			0.9 (3)		0.9	
Chlorodibromomethane				(0)			0.3 (4)			
Bromoform				(0)			9 (4)			
Dichlorodifluoromethane				(0)			0.01 (2)			
Trichlorofluoromethane				(0)			0.07 (3)			
Halogenated Ethers										
Bis(chloromethyl) Ether				(0)			ND (1)			
Bis(2-chloroethyl) Ether				(0)			<0.01 (2)			

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Bis(2-chloroisopropyl) Ether	0.1	ND	0.06	(1)			<0.01	(2)			0.07			
2-chloroethyl Vinyl Ether				(0)			0.01	(2)						
4-chlorophenyl Phenyl Ether				(0)			0.07	(2)						
4-Bromophenyl Phenyl Ether				(0)			0.01	(2)						
Bis(2-chloroethoxy) Methane				(0)			<0.01	(2)						
Monocyclic Aromatics														
Benzene	ND	0.8	0.3	(1)			0.8	(3)			1			
Chlorobenzene	ND	ND	ND	(1)			0.01	(2)			0.01			
1,2-Dichlorobenzene	0.4	0.4	0.4	(2)			0.02	(3)			0.4			
1,3-Dichlorobenzene	0.02	ND	0.01	(2)			<0.01	(2)			0.02			
1,4-Dichlorobenzene	ND	0.2	0.03	(1)			0.01	(3)			0.09			
1,2,4-Trichlorobenzene				(0)			<0.01	(2)						
Hexachlorobenzene	1	ND	0.7	(2)			0.02	(3)			0.7			
Ethylbenzene	ND	ND	ND	(1)			0.01	(3)			0.01			
Nitrobenzene				(0)			<0.01	(2)						
Toluene	2	ND	1	(1)			0.6	(5)			2			
2,4-Dinitrotoluene				(0)			0.01	(2)						
2,6-Dinitrotoluene				(0)			0.01	(2)						
Phenol	5	2	4	(2)			0.7	(6)			5			
2-Chlorophenol	2	0.5	1	(1)			<0.01	(3)			1			
2,4-Dichlorophenol	2	0.3	1	(1)			<0.01	(3)			1			
2,4,6-Tricholorophenol	3	0.3	2	(1)			0.2	(5)			2			
Pentachlorophenol	7	ND	4	(2)			0.9	(6)			5			
2-Nitrophenol				(0)			<0.01	(2)						
4-Nitrophenol				(0)			0.1	(3)						
2,4-Dinitrophenol				(0)			0.5	(2)						
2,4-Dimethyl Phenol	ND	0.2	0	(1)			<0.01	(2)			0.1			
p-Chloro-m-cresol	0.7	ND	0.4	(2)			0.01	(2)			0.4			
4,6-Dinitro-o-cresol				(0)			ND	(2)						
Phthalate Esters														
Dimethyl Phthalate				(0)			<0.01	(2)						
Diethyl Phthalate				(0)			<0.01	(3)						
Di-n-butyl Phthalate	ND	ND	ND	(1)			<0.01	(2)			<0.01			
Di-n-octyl Phthalate	ND	0.1	0.05	(1)			<0.01	(2)			0.06			
Bis(2-ethylhexyl) Phthalate	ND	2	1	(1)			0.4	(4)			1			
Butyl Benzyl Phthalate	ND	ND	ND	(1)			<0.01	(3)			<0.01			
Polycyclic Aromatic Hydrocarbons														
Acenaphthene	ND	0.04	0.02	(1)			<0.01	(3)			0.03			
Acenaphthylene				(0)			<0.01	(2)						
Fluorene	1	ND	0.6	(2)			<0.01	(3)			0.6			
Napthalene	2	0.3	1	(2)			0.5	(4)			2			
Anthracene	0.01	ND	0.01	(2)			<0.01	(3)			0.02			

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Fluoranthene	0.08	ND	0.05	(2)			<0.01	(4)			0.06		
Phenanthrene	0.03	ND	0.02	(2)			<0.01	(3)			0.03		
Benzo[a]anthracene				(0)			0.01	(4)					
Benzo[b]fluoranthene	ND	0.04	0.02	(1)			<0.01	(2)			0.03		
Benzo[k]fluoranthene	ND	0.09	0.04	(1)			<0.01	(3)			0.05		
Chrysene	0.5	0.02	0.3	(2)			0.01	(2)			0.3		
Pyrene	ND	0.1	0.04	(2)			<0.01	(3)			0.05		
Benzo[ghi]perylene				(0)			0.01	(3)					
Benzo[a]pyrene				(0)			0.01	(3)					
Dibenzo[a]anthracene	0.8	ND	0.5	(2)			0.01	(2)			0.5		
Indeno[1,2,3-cd]-pyrene				(0)			0.01	(3)					
Nitrosamines & Misc.													
N-nitrosodimethyl-amine	1	ND	0.7	(2)			0.06	(2)			0.8		
N-nitrosodiphenyl-amine				(0)			<0.01	(2)					
N-nitrosodi-n-propylamine				(0)			0.01	(2)					
Benzidine				(0)			0.06	(2)					
3,3'-Dichloro-benzidine				(0)			0.03	(2)					
1,2-Diphenylhydrazine	0.07	0.02	0.05	(2)			<0.01	(2)			0.06		
Acrylonitrile				(0)			0.02	(2)					

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Appendix D. Mass loading values calculated from available data. Number of sources contributing to each calculated value is shown in parentheses. Data for all values are given in kg/day, except where noted.

Receiving Water Southern Puget Sound	Municipal (12) Wet	Municipal (12) Dry	Municipal (12) Annual	Industrial (18) Wet	Industrial (18) Dry	Industrial (18) Annual	Total for NPDES Permitted Dischargers Wet	Total for NPDES Permitted Dischargers Dry	Total for NPDES Permitted Dischargers Annual	Nonpermitted Sources Annual[a]	Grand Total Annual
CONVENTIONAL POLLUTANT											
Flow (cubic m/d)	42,848	31,636	38,176 (6)	67,765	67,973	67,852 (8)	110,613	99,609	106,028		
Biochemical Oxygen Demand (BOD)	2,132	1,582	1,903 (7)	2,540	1,277	2,014 (2)	4,672	2,859	3,917		
Total Suspended Solids	1,905	1,254	1,634 (7)	2,483	3,006	2,700 (4)	4,388	4,260	4,334		
Oils & Grease	14	6	11 (1)	40		40 (1)	54		51		
pH (range)	6.2-7.3	6.2-7.7	6.2-7.2 (7)	3.2-9.0	6.2-11.9	3.2-11.9 (8)	3.2-9.0	6.2-11.9	3.2-11.9		
Fecal Coliform (MPN/100 ml)	0-2,600	$0-1x10^6$	$0-1x10^6$ (7)	37,400		37,400 (1)	0-37,400		$0-1x10^6$		
EXTENDED CONVENTIONAL POLLUTANT											
Chemical Oxygen Demand (COD)	1,403		1,403 (2)	11,030		11,030 (1)	12,433		12,433		
Total Solids	984		984 (1)								
Total Nonvolatile Solids	582		582 (1)								
Total Nonvolatile Suspended Solids	39		39 (1)								
Total Nitrogen	122		122 (2)	126		126 (1)	248		248		
Total Phosphorus	44		44 (2)	56		56 (1)	100		100		
PRIORITY POLLUTANT											
Heavy Metals & Inorg.											
Antimony				ND		ND (1)					
Arsenic	0.3	0.5	0.4 (6)	ND		ND (1)	0.3		0.4	4	4
Asbestos (fibers/d)		$3x10^{15}$	$3x10^{15}$ (1)			(0)					
Beryllium			(0)	ND		ND (1)					
Cadmium	0.1	0.05	0.08 (1)	ND		ND (1)	0.1		0.08	4	4
Chromium	0.5	0.3	0.4 (1)	ND		ND (1)	0.5		0.4	18	18
Copper	0.8	0.4	0.6 (1)	1		1 (1)	2		2	9	11
Cyanide			(0)	ND		ND (1)					
Lead	1	0.3	0.7 (1)	1		1 (1)	2		2	9	11
Mercury	0.01	0.2	0.09 (1)	ND		ND (1)	<0.01		0.09	0.05	0.1
Nickel	0.3	0.2	0.3 (1)	0.3		0.3 (1)	0.6		0.6	26	27
Selenium	0.3	0.5	0.4 (1)	ND		ND (1)	0.3		0.4	1	1
Silver	0.09	0.07	0.08 (1)	ND		ND (1)	0.09		0.08	0	0.08
Thallium			(0)	ND		ND (1)					
Zinc	3	2	3 (1)	7		7 (1)	10		10	45	55
Pesticides, PCBs, etc.											
Acrolein			(0)	ND		ND (1)					
Aldrin			(0)	ND		ND (1)					
Chlorodane			(0)	ND		ND (1)					
DDD			(0)	ND		ND (1)					
DDE			(0)	ND		ND (1)					
DDT			(0)	ND		ND (1)					

NOTE: [a] = Nisqually River, see Table 4-1.

Dieldrin				(0)	ND		ND (1)			
Endosulfan and Endosulfan Sulfate				(0)	ND		ND (1)			
Endrin and Endrin Aldehyde				(0)	ND		ND (1)			
Heptachlor				(0)	ND		ND (1)			
Heptachlor Epoxide				(0)	ND		ND (1)			
Hexachlorocyclohexane Isomers				(0)	ND		ND (1)			
Isophorone				(0)	ND		ND (1)			
TCDD				(0)	ND		ND (1)			
Toxaphene				(0)	ND		ND (1)			
PCBs				(0)	ND		ND (1)			
2-Chloronaphthalene				(0)	ND		ND (1)			
Halogenated Aliphatic Hydrocarbons										
Methyl Chloride				(0)	ND		ND (1)			
Methylene Chloride				(0)	ND		ND (1)			
Chloroform				(0)	ND		ND (1)			
Carbon Tetrachloride				(0)	ND		ND (1)			
Chloroethane				(0)	ND		ND (1)			
1,1-Dichloroethane				(0)	ND		ND (1)			
1,2-Dichloroethane				(0)	ND		ND (1)			
1,1,1-Trichloroethane				(0)	ND		ND (1)			
1,1,2-Trichloroethane				(0)	ND		ND (1)			
1,1,2,2-Tetrachloroethane				(0)	ND		ND (1)			
Hexachloroethane				(0)	ND		ND (1)			
Vinyl Chloride				(0)	ND		ND (1)			
1,1-Dichloroethylene				(0)	ND		ND (1)			
1,2-trans-Dichloroethylene				(0)	ND		ND (1)			
Trichloroethylene				(0)	ND		ND (1)			
Tetrachloroethylene				(0)	ND		ND (1)			
1,2-Dichloropropane				(0)	ND		ND (1)			
1,3-Dichloropropene				(0)	ND		ND (1)			
Hexachlorobutadiene				(0)	ND		ND (1)			
Hexachlorocyclopentadiene				(0)	ND		ND (1)			
Methyl Bromide				(0)	ND		ND (1)			
Dichlorobromomethane				(0)	ND		ND (1)			
Chlorodibromomethane				(0)	ND		ND (1)			
Bromoform				(0)	ND		ND (1)			
Dichlorodifluoromethane				(0)	ND		ND (1)			
Trichlorofluoromethane				(0)	ND		ND (1)			
Halogenated Ethers										
Bis(chloromethyl) Ether				(0)	ND		ND (1)			
Bis(2-chloroethyl) Ether	ND	0.01	<0.01	(1)	ND		ND (1)	ND	<0.01	

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Bis(2-chloroiso-propyl) Ether	0.03	<0.01	0.02 (1)	ND		ND (1)	0.03	0.02
2-chloroethyl Vinyl Ether			(0)	ND		ND (1)		
4-chlorophenyl Phenyl Ether			(0)	ND		ND (1)		
4-Bromophenyl Phenyl Ether			(0)	ND		ND (1)		
Bis(2-chloroethoxy) Methane			(0)	ND		ND (1)		
Monocyclic Aromatics								
Benzene			(0)	ND		ND (1)		
Chlorobenzene			(0)	ND		ND (1)		
1,2-Dichlorobenzene	0.09	ND	0.05 (1)	ND		ND (1)	0.09	0.05
1,3-Dichlorobenzene	<0.01	0.03	0.02 (1)	ND		ND (1)	<0.01	0.02
1,4-Dichlorobenzene			(0)	ND		ND (1)		
1,2,4-Trichloro-benzene			(0)	ND		ND (1)		
Hexachlorobenzene	0.07	0.03	0.05 (1)	ND		ND (1)	0.07	0.05
Ethylbenzene			(0)	ND		ND (1)		
Nitrobenzene			(0)	ND		ND (1)		
Toluene			(0)	ND		ND (1)		
2,4-Dinitrotoluene			(0)	ND		ND (1)		
2,6-Dinitrotoluene	ND	0.01	<0.01 (1)	ND		ND (1)	ND	<0.01
Phenol	0.02	ND	0.01 (1)	ND		ND (1)	0.02	0.01
2-Chlorophenol			(0)	ND		ND (1)		
2,4-Dichlorophenol			(0)	ND		ND (1)		
2,4,6-Tricholoro-phenol			(0)	ND		ND (1)		
Pentachlorophenol	0.3	ND	0.2 (1)	ND		ND (1)	0.3	0.2
2-Nitrophenol			(0)	ND		ND (1)		
4-Nitrophenol			(0)	<0.01		<0.01 (1)		
2,4-Dinitrophenol			(0)	ND		ND (1)		
2,4-Dimethyl Phenol			(0)	ND		ND (1)		
p-Chloro-m-cresol	<0.01	ND	<0.01 (1)	ND		ND (1)	<0.01	<0.01
4,6-Dinitro-o-cresol			(0)	ND		ND (1)		
Phthalate Esters								
Dimethyl Phthalate			(0)	ND		ND (1)		
Diethyl Phthalate			(0)	ND		ND (1)		
Di-n-butyl Phthalate			(0)	<0.01		<0.01 (1)		
Di-n-octyl Phthalate			(0)	ND		ND (1)		
Bis(2-ethylhexyl) Phthalate			(0)	<0.01		<0.01 (1)		
Butyl Benzyl Phthalate			(0)	ND		ND (1)		
Polycyclic Aromatic Hydrocarbons								
Acenaphthene			(0)	ND		ND (1)		
Acenaphthylene			(0)	ND		ND (1)		
Fluorene	0.2	0.05	0.01 (1)	ND		ND (1)	0.2	0.01
Napthalene	<0.01	ND	<0.01 (1)	ND		ND (1)	<0.01	<0.01
Anthracene	<0.01	ND	<0.01 (1)	ND		ND (1)	<0.01	<0.01

Fluoranthene			(0)	ND		ND (1)			
Phenanthrene	0.02	ND	0.01 (1)	ND		ND (1)	0.02		0.01
Benzo[a]anthracene	ND	0.07	0.04 (1)	ND		ND (1)	ND		0.04
Benzo[b]fluoranthene			(0)	ND		ND (1)			
Benzo[k]fluoranthene			(0)	ND		ND (1)			
Chrysene	0.03	ND	0.02 (1)	ND		ND (1)	0.03		0.02
Pyrene	0.2	ND	0.1 (1)	ND		ND (1)	0.2		0.1
Benzo[ghi]perylene			(0)	ND		ND (1)			
Benzo[a]pyrene			(0)	ND		ND (1)			
Dibenzo[a]anthracene	<0.01	ND	<0.01 (1)	ND		ND (1)	<0.01		<0.01
Indeno[1,2,3-cd]-pyrene			(0)	ND		ND (1)			
Nitrosamines & Misc.									
N-nitrosodimethylamine	ND	0.08	0.03 (1)	ND		ND (1)	ND		0.03
N-nitrosodiphenylamine			(0)	ND		ND (1)			
N-nitrosodi-n-propylamine	<0.01	ND	<0.01 (1)	ND		ND (1)	<0.01		<0.01
Benzidine			(0)	ND		ND (1)			
3,3'-Dichlorobenzidine			(0)	ND		ND (1)			
1,2-Diphenylhydrazine	<0.01	ND	<0.01 (1)	ND		ND (1)	<0.01		<0.01
Acrylonitrile			(0)	ND		ND (1)			

Appendix D. Mass loading values calculated from available data. Number of sources contributing to each calculated value is shown in parentheses. Data for all values are given in kg/day, except where noted.

Receiving Water	Municipal (4) Wet	Municipal (4) Dry	Municipal (4) Annual	Industrial (3) Wet	Industrial (3) Dry	Industrial (3) Annual	Total for NPDES Permitted Dischargers Wet	Total for NPDES Permitted Dischargers Dry	Total for NPDES Permitted Dischargers Annual	Nonpermitted Sources Annual	Grand Total Annual
Budd Inlet											
CONVENTIONAL POLLUTANT											
Flow (cubic m/d)	31,969	31,939	31,954 (4)			(0)					
Biochemical Oxygen Demand (BOD)			561 (2)			(0)					
Total Suspended Solids			606 (3)			(0)					
Oils & Grease			(0)			(0)					
pH (range)	6.5-7.1	6.5-7.1	6.5-7.1 (1)								
Fecal Coliform (MPN/100 ml)	12	7-262	7-262 (2)			(0)					
EXTENDED CONVENTIONAL POLLUTANT											
Chemical Oxygen Demand (COD)		1,558	1,558 (1)			(0)					
Total Solids			(0)			(0)					
Total Nonvolatile Solids			(0)			(0)					
Total Nonvolatile Suspended Solids			(0)			(0)					
Total Nitrogen		318	318 (1)			(0)					
Total Phosphorus		272	272 (1)								
PRIORITY POLLUTANT											
Heavy Metals & Inorg.						(0)					
Antimony			(0)			(0)					
Arsenic			(0)			(0)					
Asbestos (fibers/d)			(0)			(0)					
Beryllium			(0)			(0)					
Cadmium			(0)			(0)					
Chromium			(0)			(0)					
Copper			(0)			(0)					
Cyanide			(0)			(0)					
Lead			(0)			(0)					
Mercury			(0)			(0)					
Nickel			(0)			(0)					
Selenium			(0)			(0)					
Silver			(0)			(0)					
Thallium			(0)			(0)					
Zinc			(0)			(0)					
Pesticides, PCBs, etc.											
Acrolein			(0)			(0)					
Aldrin			(0)			(0)					
Chlorodane			(0)			(0)					
DDD			(0)			(0)					
DDE			(0)			(0)					
DDT			(0)			(0)					

Dieldrin			(0)			(0)					
Endosulfan and Endosulfan Sulfate			(0)			(0)					
Endrin and Endrin Aldehyde			(0)			(0)					
Heptachlor			(0)			(0)					
Heptachlor Epoxide			(0)			(0)					
Hexachlorocyclohexane Isomers			(0)			(0)					
Isophorone			(0)			(0)					
TCDD			(0)			(0)					
Toxaphene			(0)			(0)					
PCBs			(0)			(0)					
2-Chloronaphthalene			(0)			(0)					
Halogenated Aliphatic Hydrocarbons			(0)			(0)					
Methyl Chloride			(0)			(0)					
Methylene Chloride			(0)			(0)					
Chloroform			(0)			(0)					
Carbon Tetrachloride			(0)			(0)					
Chloroethane			(0)			(0)					
1,1-Dichloroethane			(0)			(0)					
1,2-Dichloroethane			(0)			(0)					
1,1,1-Trichloroethane			(0)			(0)					
1,1,2-Trichloroethane			(0)			(0)					
1,1,2,2-Tetrachloroethane			(0)			(0)					
Hexachloroethane			(0)			(0)					
Vinyl Chloride			(0)			(0)					
1,1-Dichloroethylene			(0)			(0)					
1,2-trans-Dichloroethylene			(0)			(0)					
Trichloroethylene			(0)			(0)					
Tetrachloroethylene			(0)			(0)					
1,2-Dichloropropane			(0)			(0)					
1,3-Dichloropropene			(0)			(0)					
Hexachlorobutadiene			(0)			(0)					
Hexachlorocyclopentadiene			(0)			(0)					
Methyl Bromide			(0)			(0)					
Dichlorobromomethane			(0)			(0)					
Chlorodibromomethane			(0)			(0)					
Bromoform			(0)			(0)					
Dichlorodifluoromethane			(0)			(0)					
Trichlorofluoromethane			(0)			(0)					
Halogenated Ethers											
Bis(chloromethyl) Ether			(0)			(0)					
Bis(2-chloroethyl) Ether			(0)			(0)					

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Bis(2-chloroisopropyl) Ether										
2-chloroethyl Vinyl Ether			(0)			(0)				
4-chlorophenyl Phenyl Ether			(0)			(0)				
4-Bromophenyl Phenyl Ether			(0)			(0)				
Bis(2-chloroethoxy) Methane			(0)			(0)				
			(0)			(0)				
Monocyclic Aromatics										
Benzene			(0)			(0)				
Chlorobenzene			(0)			(0)				
1,2-Dichlorobenzene			(0)			(0)				
1,3-Dichlorobenzene			(0)			(0)				
1,4-Dichlorobenzene			(0)			(0)				
1,2,4-Trichlorobenzene			(0)			(0)				
Hexachlorobenzene			(0)			(0)				
Ethylbenzene			(0)			(0)				
Nitrobenzene			(0)			(0)				
Toluene			(0)			(0)				
2,4-Dinitrotoluene			(0)			(0)				
2,6-Dinitrotoluene			(0)			(0)				
Phenol			(0)			(0)				
2-Chlorophenol			(0)			(0)				
2,4-Dichlorophenol			(0)			(0)				
2,4,6-Tricholorophenol			(0)			(0)				
Pentachlorophenol			(0)			(0)				
2-Nitrophenol			(0)			(0)				
4-Nitrophenol			(0)			(0)				
2,4-Dinitrophenol			(0)			(0)				
2,4-Dimethyl Phenol			(0)			(0)				
p-Chloro-m-cresol			(0)			(0)				
4,6-Dinitro-o-cresol			(0)			(0)				
			(0)			(0)				
Phthalate Esters										
Dimethyl Phthalate			(0)			(0)				
Diethyl Phthalate			(0)			(0)				
Di-n-butyl Phthalate			(0)			(0)				
Di-n-octyl Phthalate			(0)			(0)				
Bis(2-ethylhexyl) Phthalate			(0)			(0)				
Butyl Benzyl Phthalate			(0)			(0)				
			(0)			(0)				
Polycyclic Aromatic Hydrocarbons										
Acenaphthene			(0)			(0)				
Acenaphthylene			(0)			(0)				
Fluorene			(0)			(0)				
Naphthalene			(0)			(0)				
Anthracene			(0)			(0)				

Fluoranthene			(0)			(0)					
Phenanthrene			(0)			(0)					
Benzo[a]anthracene			(0)			(0)					
Benzo[b]fluoranthene			(0)			(0)					
Benzo[k]fluoranthene			(0)			(0)					
Chrysene			(0)			(0)					
Pyrene			(0)			(0)					
Benzo[ghi]perylene			(0)			(0)					
Benzo[a]pyrene			(0)			(0)					
Dibenzo[a]anthracene			(0)			(0)					
Indeno[1,2,3-cd]-pyrene			(0)			(0)					
Nitrosamines & Misc.											
N-nitrosodimethyl-amine			(0)			(0)					
N-nitrosodiphenyl-amine			(0)			(0)					
N-nitrosodi-n-propylamine			(0)			(0)					
Benzidine			(0)			(0)					
3,3'-Dichloro-benzidine			(0)			(0)					
1,2-Diphenylhydrazine			(0)			(0)					
Acrylonitrile			(0)			(0)					

Appendix D. Mass loading values calculated from available data. Number of sources contributing to each calculated value is shown in parentheses. Data for all values are given in kg/day, except where noted.

Receiving Water Hood Canal	Municipal (2) Wet	Municipal (2) Dry	Municipal (2) Annual	Industrial (7) Wet	Industrial (7) Dry	Industrial (7) Annual	Total for NPDES Permitted Dischargers Wet	Total for NPDES Permitted Dischargers Dry	Total for NPDES Permitted Dischargers Annual	Nonpermitted Sources Annual	Grand Total Annual
CONVENTIONAL POLLUTANT											
Flow (cubic m/d)	144	174	156 (2)	2,461		2,461 (1)	2,605		2,617		
Biochemical Oxygen Demand (BOD)	1	1	1 (2)	17		17 (1)	18		18		
Total Suspended Solids	1	1	1 (2)	12		12 (1)	13		13		
Oils & Grease			(0)			(0)					
pH (range)	6.6-7.0	6.6-7.0	6.6-7.0 (2)	6.0-9.3		6.0-9.3 (1)	6.0-9.3		6.0-9.3		
Fecal Coliform (MPN/100 ml)	0-4	0-98	0-98 (2)			(0)					
EXTENDED CONVENTIONAL POLLUTANT											
Chemical Oxygen Demand (COD)			(0)			(0)					
Total Solids			(0)			(0)					
Total Nonvolatile Solids			(0)			(0)					
Total Nonvolatile Suspended Solids			(0)			(0)					
Total Nitrogen			(0)			(0)					
Total Phosphorus			(0)			(0)					
PRIORITY POLLUTANT											
Heavy Metals & Inorg.			(0)			(0)					
Antimony			(0)			(0)					
Arsenic			(0)			(0)					
Asbestos (fibers/d)			(0)			(0)					
Beryllium			(0)			(0)					
Cadmium			(0)			(0)					
Chromium			(0)			(0)					
Copper			(0)			(0)					
Cyanide			(0)			(0)					
Lead			(0)			(0)					
Mercury			(0)			(0)					
Nickel			(0)			(0)					
Selenium			(0)			(0)					
Silver			(0)			(0)					
Thallium			(0)			(0)					
Zinc			(0)			(0)					
Pesticides, PCBs, etc.											
Acrolein			(0)			(0)					
Aldrin			(0)			(0)					
Chlorodane			(0)			(0)					
DDD			(0)			(0)					
DDE			(0)			(0)					
DDT			(0)			(0)					

Dieldrin			(0)			(0)				
Endosulfan and Endosulfan Sulfate			(0)			(0)				
Endrin and Endrin Aldehyde			(0)			(0)				
Heptachlor			(0)			(0)				
Heptachlor Epoxide			(0)			(0)				
Hexachlorocyclohexane Isomers			(0)			(0)				
Isophorone			(0)			(0)				
TCDD			(0)			(0)				
Toxaphene			(0)			(0)				
PCBs			(0)			(0)				
2-Chloronaphthalene			(0)			(0)				
Halogenated Aliphatic Hydrocarbons										
Methyl Chloride			(0)			(0)				
Methylene Chloride			(0)			(0)				
Chloroform			(0)			(0)				
Carbon Tetrachloride			(0)			(0)				
Chloroethane			(0)			(0)				
1,1-Dichloroethane			(0)			(0)				
1,2-Dichloroethane			(0)			(0)				
1,1,1-Trichloroethane			(0)			(0)				
1,1,2-Trichloroethane			(0)			(0)				
1,1,2,2-Tetrachloroethane			(0)			(0)				
Hexachloroethane			(0)			(0)				
Vinyl Chloride			(0)			(0)				
1,1-Dichloroethylene			(0)			(0)				
1,2-trans-Dichloroethylene			(0)			(0)				
Trichloroethylene			(0)			(0)				
Tetrachloroethylene			(0)			(0)				
1,2-Dichloropropane			(0)			(0)				
1,3-Dichloropropene			(0)			(0)				
Hexachlorobutadiene			(0)			(0)				
Hexachlorocyclopentadiene			(0)			(0)				
Methyl Bromide			(0)			(0)				
Dichlorobromomethane			(0)			(0)				
Chlorodibromomethane			(0)			(0)				
Bromoform			(0)			(0)				
Dichlorodifluoromethane			(0)			(0)				
Trichlorofluoromethane			(0)			(0)				
Halogenated Ethers										
Bis(chloromethyl) Ether			(0)			(0)				
Bis(2-chloroethyl) Ether			(0)			(0)				

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Bis(2-chloroiso-propyl) Ether			(0)			(0)					
2-chloroethyl Vinyl Ether			(0)			(0)					
4-chlorophenyl Phenyl Ether			(0)			(0)					
4-Bromophenyl Phenyl Ether			(0)			(0)					
Bis(2-chloroethoxy) Methane			(0)			(0)					
Monocyclic Aromatics											
Benzene			(0)			(0)					
Chlorobenzene			(0)			(0)					
1,2-Dichlorobenzene			(0)			(0)					
1,3-Dichlorobenzene			(0)			(0)					
1,4-Dichlorobenzene			(0)			(0)					
1,2,4-Trichloro-benzene			(0)			(0)					
Hexachlorobenzene			(0)			(0)					
Ethylbenzene			(0)			(0)					
Nitrobenzene			(0)			(0)					
Toluene			(0)			(0)					
2,4-Dinitrotoluene			(0)			(0)					
2,6-Dinitrotoluene			(0)			(0)					
Phenol			(0)			(0)					
2-Chlorophenol			(0)			(0)					
2,4-Dichlorophenol			(0)			(0)					
2,4,6-Tricholoro-phenol			(0)			(0)					
Pentachlorophenol			(0)			(0)					
2-Nitrophenol			(0)			(0)					
4-Nitrophenol			(0)			(0)					
2,4-Dinitrophenol			(0)			(0)					
2,4-Dimethyl Phenol			(0)			(0)					
p-Chloro-m-cresol			(0)			(0)					
4,6-Dinitro-o-cresol			(0)			(0)					
Phthalate Esters											
Dimethyl Phthalate			(0)			(0)					
Diethyl Phthalate			(0)			(0)					
Di-n-butyl Phthalate			(0)			(0)					
Di-n-octyl Phthalate			(0)			(0)					
Bis(2-ethylhexyl) Phthalate			(0)			(0)					
Butyl Benzyl Phthalate			(0)			(0)					
Polycyclic Aromatic Hydrocarbons											
Acenaphthene			(0)			(0)					
Acenaphthylene			(0)			(0)					
Fluorene			(0)			(0)					
Napthalene			(0)			(0)					
Anthracene			(0)			(0)					

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Fluoranthene			(0)			(0)				
Phenanthrene			(0)			(0)				
Benzo[a]anthracene			(0)			(0)				
Benzo[b]fluoranthene			(0)			(0)				
Benzo[k]fluoranthene			(0)			(0)				
Chrysene			(0)			(0)				
Pyrene			(0)			(0)				
Benzo[ghi]perylene			(0)			(0)				
Benzo[a]pyrene			(0)			(0)				
Dibenzo[a]anthracene			(0)			(0)				
Indeno[1,2,3-cd]-pyrene			(0)			(0)				
Nitrosamines & Misc.										
N-nitrosodimethylamine			(0)			(0)				
N-nitrosodiphenylamine			(0)			(0)				
N-nitrosodi-n-propylamine			(0)			(0)				
Benzidine			(0)			(0)				
3,3'-Dichlorobenzidine			(0)			(0)				
1,2-Diphenylhydrazine			(0)			(0)				
Acrylonitrile			(0)			(0)				

Appendix D. Mass loading values calculated from available data. Number of sources contributing to each calculated value is shown in parentheses. Data for all values are given in kg/day, except where noted.

Receiving Water	Municipal (1) Wet	Municipal (1) Dry	Municipal (1) Annual	Industrial (6) Wet	Industrial (6) Dry	Industrial (6) Annual	Total for NPDES Permitted Dischargers Wet	Total for NPDES Permitted Dischargers Dry	Total for NPDES Permitted Dischargers Annual	Nonpermitted Sources Annual	Grand Total Annual
Port Angeles											
CONVENTIONAL POLLUTANT											
Flow (cubic m/d)	15,899	7,647	12,460 (1)	183,144	159,470	173,279 (3)	199,043	167,117	185,739		
Biochemical Oxygen Demand (BOD)	898	581	762 (1)	21,864	18,462	20,458 (2)	22,762	19,043	21,220		
Total Suspended Solids	821	499	685 (1)	19,365	17,419	18,553 (2)	20,186	17,918	19,238		
Oils & Grease			(0)	296	695	462 (1)					
pH (range)	6.8-7.1	6.5-7.0	6.5-7.1 (1)	4.0-10.0	4.0-9.5	4.0-10.0 (2)	4.0-10.0	4.0-9.5	4.0-10.0		
Fecal Coliform (MPN/100 ml)	275-500	700	275-700 (1)	15,750-40,000		15,750-40,000 (2)	275-40,000		275-40,000		
EXTENDED CONVENTIONAL POLLUTANT											
Chemical Oxygen Demand (COD)			(0)	103,334		103,334 (2)					
Total Solids			(0)	265,684		265,684 (2)					
Total Nonvolatile Solids			(0)	170,560		170,560 (2)					
Total Nonvolatile Suspended Solids			(0)	4,400		4,400 (2)					
Total Nitrogen			(0)	2,789		2,789 (2)					
Total Phosphorus			(0)	866		866 (2)					
PRIORITY POLLUTANT											
Heavy Metals & Inorg.											
Antimony			(0)	0.3		0.3 (1)					
Arsenic			(0)	0.4		0.4 (1)					
Asbestos (fibers/d)			(0)			(0)					
Beryllium			(0)	0.3		0.3 (1)					
Cadmium			(0)	2		2 (2)					
Chromium			(0)	18		18 (2)					
Copper			(0)	4		4 (2)					
Cyanide			(0)	0.3		0.3 (1)					
Lead			(0)	8		8 (2)					
Mercury			(0)	0.01		0.01 (1)					
Nickel			(0)	8		8 (2)					
Selenium			(0)	0.3		0.3 (1)					
Silver			(0)	0.2		0.2 (1)					
Thallium			(0)	0.4		0.4 (1)					
Zinc			(0)	16	27	20 (2)					
Pesticides, PCBs, etc.											
Acrolein			(0)	ND		ND (1)					
Aldrin			(0)	ND		ND (1)					
Chlorodane			(0)	ND		ND (1)					
DDD			(0)	ND		ND (1)					
DDE			(0)	ND		ND (1)					
DDT			(0)	ND		ND (1)					

Dieldrin			(0)	ND		ND	(1)			
Endosulfan and Endosulfan Sulfate			(0)	ND		ND	(1)			
Endrin and Endrin Aldehyde			(0)	ND		ND	(1)			
Heptachlor			(0)	ND		ND	(1)			
Heptachlor Epoxide			(0)	ND		ND	(1)			
Hexachlorocyclohexane Isomers			(0)	ND		ND	(1)			
Isophorone			(0)	ND		ND	(1)			
TCDD			(0)	ND		ND	(1)			
Toxaphene			(0)	ND		ND	(1)			
PCBs			(0)	ND		ND	(1)			
2-Chloronaphthalene			(0)	ND		ND	(1)			
Halogenated Aliphatic Hydrocarbons										
Methyl Chloride			(0)	ND		ND	(1)			
Methylene Chloride			(0)	ND		ND	(1)			
Chloroform			(0)	ND		ND	(1)			
Carbon Tetrachloride			(0)	ND		ND	(1)			
Chloroethane			(0)	ND		ND	(1)			
1,1-Dichloroethane			(0)	ND		ND	(1)			
1,2-Dichloroethane			(0)	ND		ND	(1)			
1,1,1-Trichloroethane			(0)	ND		ND	(1)			
1,1,2-Trichloroethane			(0)	ND		ND	(1)			
1,1,2,2-Tetrachloroethane			(0)	ND		ND	(1)			
Hexachloroethane			(0)	ND		ND	(1)			
Vinyl Chloride			(0)	ND		ND	(1)			
1,1-Dichloroethylene			(0)	ND		ND	(1)			
1,2-trans-Dichloroethylene			(0)	ND		ND	(1)			
Trichloroethylene			(0)	ND		ND	(1)			
Tetrachloroethylene			(0)	ND		ND	(1)			
1,2-Dichloropropane			(0)	ND		ND	(1)			
1,3-Dichloropropene			(0)	ND		ND	(1)			
Hexachlorobutadiene			(0)	ND		ND	(1)			
Hexachlorocyclopentadiene			(0)	ND		ND	(1)			
Methyl Bromide			(0)	ND		ND	(1)			
Dichlorobromomethane			(0)	ND		ND	(1)			
Chlorodibromomethane			(0)	ND		ND	(1)			
Bromoform			(0)	ND		ND	(1)			
Dichlorodifluoromethane			(0)	ND		ND	(1)			
Trichlorofluoromethane			(0)	ND		ND	(1)			
Halogenated Ethers										
Bis(chloromethyl) Ether			(0)	ND		ND	(1)			
Bis(2-chloroethyl) Ether			(0)	ND		ND	(1)			

Bis(2-chloroiso-propyl) Ether			(0)	ND		ND	(1)				
2-chloroethyl Vinyl Ether			(0)	ND		ND	(1)				
4-chlorophenyl Phenyl Ether			(0)	ND		ND	(1)				
4-Bromophenyl Phenyl Ether			(0)	ND		ND	(1)				
Bis(2-chloroethoxy) Methane			(0)	ND		ND	(1)				
Monocyclic Aromatics											
Benzene			(0)	ND		ND	(1)				
Chlorobenzene			(0)	ND		ND	(1)				
1,2-Dichlorobenzene			(0)	ND		ND	(1)				
1,3-Dichlorobenzene			(0)	ND		ND	(1)				
1,4-Dichlorobenzene			(0)	ND		ND	(1)				
1,2,4-Trichloro-benzene			(0)	ND		ND	(1)				
Hexachlorobenzene			(0)	ND		ND	(1)				
Ethylbenzene			(0)	ND		ND	(1)				
Nitrobenzene			(0)	ND		ND	(1)				
Toluene			(0)	ND		ND	(1)				
2,4-Dinitrotoluene			(0)	ND		ND	(1)				
2,6-Dinitrotoluene			(0)	ND		ND	(1)				
Phenol			(0)	ND		ND	(1)				
2-Chlorophenol			(0)	ND		ND	(1)				
2,4-Dichlorophenol			(0)	ND		ND	(1)				
2,4,6-Tricholoro-phenol			(0)	ND		ND	(1)				
Pentachlorophenol			(0)	ND		ND	(1)				
2-Nitrophenol			(0)	ND		ND	(1)				
4-Nitrophenol			(0)	ND		ND	(1)				
2,4-Dinitrophenol			(0)	ND		ND	(1)				
2,4-Dimethyl Phenol			(0)	ND		ND	(1)				
p-Chloro-m-cresol			(0)	ND		ND	(1)				
4,6-Dinitro-o-cresol			(0)	ND		ND	(1)				
Phthalate Esters											
Dimethyl Phthalate			(0)	ND		ND	(1)				
Diethyl Phthalate			(0)	0.9		0.9	(1)				
Di-n-butyl Phthalate			(0)	ND		ND	(1)				
Di-n-octyl Phthalate			(0)	ND		ND	(1)				
Bis(2-ethylhexyl) Phthalate			(0)	ND		ND	(1)				
Butyl Benzyl Phthalate			(0)	ND		ND	(1)				
Polycyclic Aromatic Hydrocarbons											
Acenaphthene			(0)	ND		ND	(1)				
Acenaphthylene			(0)	ND		ND	(1)				
Fluorene			(0)	ND		ND	(1)				
Napthalene			(0)	ND		ND	(1)				
Anthracene			(0)	ND		ND	(1)				

3

Fluoranthene										
Phenanthrene			(0)	ND		ND (1)				
Benzo[a]anthracene			(0)	ND		ND (1)				
Benzo[b]fluoranthene			(0)	ND		ND (1)				
Benzo[k]fluoranthene			(0)	ND		ND (1)				
Chrysene			(0)	ND		ND (1)				
Pyrene			(0)	ND		ND (1)				
Benzo[ghi]perylene			(0)	ND		ND (1)				
Benzo[a]pyrene			(0)	ND		ND (1)				
Dibenzo[a]anthracene			(0)	ND		ND (1)				
Indeno[1,2,3-cd]-pyrene			(0)	ND		ND (1)				
			(0)	ND		ND (1)				
Nitrosamines & Misc.										
N-nitrosodimethylamine			(0)	ND		ND (1)				
N-nitrosodiphenylamine			(0)	ND		ND (1)				
N-nitrosodi-n-propylamine			(0)	ND		ND (1)				
Benzidine			(0)	ND		ND (1)				
3,3'-Dichlorobenzidine			(0)	ND		ND (1)				
1,2-Diphenylhydrazine			(0)	ND		ND (1)				
Acrylonitrile			(0)	ND		ND (1)				

Appendix D. Mass loading values calculated from available data. Number of sources contributing to each calculated value is shown in parentheses. Data for all values are given in kg/day, except where noted.

Receiving Water San Juan Islands	Municipal (4) Wet	Municipal (4) Dry	Municipal (4) Annual	Industrial (5) Wet	Industrial (5) Dry	Industrial (5) Annual	Total for NPDES Permitted Dischargers Wet	Total for NPDES Permitted Dischargers Dry	Total for NPDES Permitted Dischargers Annual	Nonpermitted Sources Annual	Grand Total Annual
CONVENTIONAL POLLUTANT											
Flow (cubic m/d)	375	367	371 (4)	231	258	242 (3)	606	625	613		
Biochemical Oxygen Demand (BOD)	6	7	6 (3)	8	9	8 (3)	14	16	14		
Total Suspended Solids	6	7	6 (2)	2	2	2 (2)	8	9	8		
Oils & Grease			(0)			(0)					
pH (range)	6.8-7.2	6.2-7.4	6.2-7.4 (3)	5.5-7.6	6.5-7.4	5.5-7.6 (3)	5.5-7.6	6.2-7.4	5.5-7.6		
Fecal Coliform (MPN/100 ml)	22	21	21-22 (1)	180-19,000	0-22,000	0-22,000 (2)	22-19,000	0-22,000	0-22,000		
EXTENDED CONVENTIONAL POLLUTANT											
Chemical Oxygen Demand (COD)			(0)			(0)					
Total Solids			(0)			(0)					
Total Nonvolatile Solids			(0)			(0)					
Total Nonvolatile Suspended Solids			(0)			(0)					
Total Nitrogen			(0)			(0)					
Total Phosphorus			(0)			(0)					
PRIORITY POLLUTANT											
Heavy Metals & Inorg.											
Antimony			(0)			(0)					
Arsenic			(0)			(0)					
Asbestos (fibers/d)			(0)			(0)					
Beryllium			(0)			(0)					
Cadmium			(0)			(0)					
Chromium			(0)			(0)					
Copper			(0)			(0)					
Cyanide			(0)			(0)					
Lead			(0)			(0)					
Mercury			(0)			(0)					
Nickel			(0)			(0)					
Selenium			(0)			(0)					
Silver			(0)			(0)					
Thallium			(0)			(0)					
Zinc			(0)			(0)					
Pesticides, PCBs, etc.											
Acrolein			(0)			(0)					
Aldrin			(0)			(0)					
Chlorodane			(0)			(0)					
DDD			(0)			(0)					
DDE			(0)			(0)					
DDT			(0)			(0)					

Dieldrin			(0)			(0)				
Endosulfan and Endosulfan Sulfate			(0)			(0)				
Endrin and Endrin Aldehyde			(0)			(0)				
Heptachlor			(0)			(0)				
Heptachlor Epoxide			(0)			(0)				
Hexachlorocyclohexane Isomers			(0)			(0)				
Isophorone			(0)			(0)				
TCDD			(0)			(0)				
Toxaphene			(0)			(0)				
PCBs			(0)			(0)				
2-Chloronaphthalene			(0)			(0)				
Halogenated Aliphatic Hydrocarbons										
Methyl Chloride			(0)			(0)				
Methylene Chloride			(0)			(0)				
Chloroform			(0)			(0)				
Carbon Tetrachloride			(0)			(0)				
Chloroethane			(0)			(0)				
1,1-Dichloroethane			(0)			(0)				
1,2-Dichloroethane			(0)			(0)				
1,1,1-Trichloroethane			(0)			(0)				
1,1,2-Trichloroethane			(0)			(0)				
1,1,2,2-Tetrachloroethane			(0)			(0)				
Hexachloroethane			(0)			(0)				
Vinyl Chloride			(0)			(0)				
1,1-Dichloroethylene			(0)			(0)				
1,2-trans-Dichloroethylene			(0)			(0)				
Trichloroethylene			(0)			(0)				
Tetrachloroethylene			(0)			(0)				
1,2-Dichloropropane			(0)			(0)				
1,3-Dichloropropene			(0)			(0)				
Hexachlorobutadiene			(0)			(0)				
Hexachlorocyclopentadiene			(0)			(0)				
Methyl Bromide			(0)			(0)				
Dichlorobromomethane			(0)			(0)				
Chlorodibromomethane			(0)			(0)				
Bromoform			(0)			(0)				
Dichlorodifluoromethane			(0)			(0)				
Trichlorofluoromethane			(0)			(0)				
Halogenated Ethers										
Bis(chloromethyl) Ether			(0)			(0)				
Bis(2-chloroethyl) Ether			(0)			(0)				

2

Bis(2-chloroiso-propyl) Ether			(0)			(0)				
2-chloroethyl Vinyl Ether			(0)			(0)				
4-chlorophenyl Phenyl Ether			(0)			(0)				
4-Bromophenyl Phenyl Ether			(0)			(0)				
Bis(2-chloroethoxy) Methane			(0)			(0)				
Monocyclic Aromatics										
Benzene			(0)			(0)				
Chlorobenzene			(0)			(0)				
1,2-Dichlorobenzene			(0)			(0)				
1,3-Dichlorobenzene			(0)			(0)				
1,4-Dichlorobenzene			(0)			(0)				
1,2,4-Trichloro-benzene			(0)			(0)				
Hexachlorobenzene			(0)			(0)				
Ethylbenzene			(0)			(0)				
Nitrobenzene			(0)			(0)				
Toluene			(0)			(0)				
2,4-Dinitrotoluene			(0)			(0)				
2,6-Dinitrotoluene			(0)			(0)				
Phenol			(0)			(0)				
2-Chlorophenol			(0)			(0)				
2,4-Dichlorophenol			(0)			(0)				
2,4,6-Tricholoro-phenol			(0)			(0)				
Pentachlorophenol			(0)			(0)				
2-Nitrophenol			(0)			(0)				
4-Nitrophenol			(0)			(0)				
2,4-Dinitrophenol			(0)			(0)				
2,4-Dimethyl Phenol			(0)			(0)				
p-Chloro-m-cresol			(0)			(0)				
4,6-Dinitro-o-cresol			(0)			(0)				
Phthalate Esters										
Dimethyl Phthalate			(0)			(0)				
Diethyl Phthalate			(0)			(0)				
Di-n-butyl Phthalate			(0)			(0)				
Di-n-octyl Phthalate			(0)			(0)				
Bis(2-ethylhexyl) Phthalate			(0)			(0)				
Butyl Benzyl Phthalate			(0)			(0)				
Polycyclic Aromatic Hydrocarbons										
Acenaphthene			(0)			(0)				
Acenaphthylene			(0)			(0)				
Fluorene			(0)			(0)				
Naphthalene			(0)			(0)				
Anthracene			(0)			(0)				

Fluoranthene			(0)			(0)				
Phenanthrene			(0)			(0)				
Benzo[a]anthracene			(0)			(0)				
Benzo[b]fluoranthene			(0)			(0)				
Benzo[k]fluoranthene			(0)			(0)				
Chrysene			(0)			(0)				
Pyrene			(0)			(0)				
Benzo[ghi]perylene			(0)			(0)				
Benzo[a]pyrene			(0)			(0)				
Dibenzo[a]anthracene			(0)			(0)				
Indeno[1,2,3-cd]-pyrene			(0)			(0)				
Nitrosamines & Misc.										
N-nitrosodimethylamine			(0)			(0)				
N-nitrosodiphenylamine			(0)			(0)				
N-nitrosodi-n-propylamine			(0)			(0)				
Benzidine			(0)			(0)				
3,3'-Dichlorobenzidine			(0)			(0)				
1,2-Diphenylhydrazine			(0)			(0)				
Acrylonitrile			(0)			(0)				

APPENDIX E

Summary of Knowledge Regarding Transport, Fate, and Approximate Sampling Compartments for Priority Pollutants

Chemical	Importance in Aquatic Transport[a]			Importance in Determining Aquatic Fate[a]				Initial Environmental Compartment for Sampling[b]	Primary Concerns Identified in Puget Sound at Present
	Volatilization	Sorption	Transport downstream	Photolysis/Oxidation	Chemical speciation	Bioaccumulation	Biotransformation/ Biodegradation		
Metals and Inorganics									Konasewich[c] primary contaminants of concern: lead, copper, mercury, selenium, and silver.
Antimony	U(2)	YES(2)	YES(2)	NO(3)	YES(1)	NO(2)	YES(3)	W	
Arsenic	YES(1)	YES(1)	YES(1)	NO(3)	YES(1)	YES(2)	YES(1)	S,B	
Asbestos	NO(3)	NO(2)	YES(1)	NO(3)	NO(2)	NO(3)	NO(3)	W	
Beryllium	NO(3)	YES(3)	YES(3)	NO(3)	YES(2)	U(2)	NO(3)	S,B	Dexter[d] places most importance on arsenic, antimony, copper, zinc, lead, and mercury (primarily because data of sufficient quantity and quality indicate very high local concentrations).
Cadmium	NO(2)	YES(1)	YES(1)	NO(3)	YES(1)	YES(1)	NO(3)	S,B	
Chromium	NO(3)	YES(1)	YES(2)	NO(3)	YES(2)	YES(1)	NO(3)	S,B	
Copper	NO(3)	YES(1)	YES(1)	NO(2)	YES(1)	YES(1)	NO(3)	S,B	
Cyanide	YES(1)	NO(2)	NO(2)	YES(1)	U(2)	NO(2)	YES(1)	W	
Lead	U(1)	YES(1)	YES(1)	U(1)	YES(1)	YES(1)	YES(1)	S,B	
Mercury	YES(1)	YES(1)	YES(1)	YES(2)	YES(1)	YES(1)	YES(1)	S,B	
Nickel	NO(3)	YES(1)	YES(1)	NO(3)	YES(2)	NO(2)	NO(3)	S,B	
Selenium	U(2)	YES(1)	YES(1)	NO(3)	YES(2)	U(1)	YES(1)	S,B	Crecelius[e] metals of some concern (based upon elevated levels in biota sediments and water) include silver, mercury, lead, and copper.
Silver	NO(3)	YES(1)	YES(1)	NO(2)	YES(1)	U(1)	NO(3)	S,B	
Thallium	NO(3)	YES(1)	YES(1)	NO(2)	YES(1)	U(2)	NO(3)	S,B	
Zinc	NO(3)	YES(1)	YES(1)	NO(3)	YES(1)	YES(1)	NO(3)	S,B	
Pesticides, PCBs, and Related Compounds					Hydrolysis				
Acrolein	U(2)	NO(2)	U(2)	U(2)	NO(1)	U(2)	YES(2)	S,B	Konasewich[c] primary contaminants of concern: DDT and metabolites DDD, DDE, PCBs.
Aldrin	U(2)	YES(2)	U(2)	U(2)	NO(1)	YES(1)	YES(2)	W,B	
Chlordane	U(2)	U(2)	U(2)	U(2)	NO(1)	YES(1)	U(2)	S,B	
DDD	YES(2)	YES(1)	U(2)	U(2)	U(1)	YES(1)	U(2)	S,B	
DDE	YES(2)	YES(1)	U(2)	U(2)	NO(1)	YES(1)	U(2)	S,B	
DDT	YES(2)	YES(1)	U(2)	U(2)	U(1)	YES(1)	U(2)	S,B	
Dieldrin	U(2)	YES(2)	U(2)	U(2)	NO(1)	YES(1)	U(2)	S,B	
Endosulfan and Endosulfan Sulfate	U(3)	YES(3)	U(3)	U(2)	YES(1)	U(2)	YES(2)	S	
Endrin and Endrin Aldehyde	U(2)	U(2)	U(2)	U(2)	NO(1)	YES(1)	U(2)	W,S,B	
Heptachlor	U(2)	NO(2)	U(2)	U(2)	YES(1)	U(1)	NO(1)	S,B	
Heptachlor Epoxide	U(2)	YES(1)	U(2)	U(2)	NO(1)	YES(1)	YES(2)	W,S,B	
Hexachlorocyclohexane (α, β, δ isomers)	U(2)	U(2)	U(2)	NO(1)	NO(1)	U(1)	YES(2)	W,S	
γ-Hexachlorocyclohexane (Lindane)	U(2)	U(2)	U(1)	NO(1)	NO(1)	U(1)	YES(2)	W,S	

APPENDIX E (Continued)

Chemical	Importance in Aquatic Transport[a]			Importance in Determining Aquatic Fate[a]				Initial Environmental Compartment for Sampling[b]	Primary Concerns Identified in Puget Sound at Present
	Volatilization	Sorption	Transport downstream	Photolysis/Oxidation	Hydrolysis	Bioaccumulation	Biotransformation/ Biodegradation		
Isophorone	U(3)	NO(3)	YES(3)	U(2)	NO(1)	U(2)	U(2)	W	
TCDD	U(2)	YES(1)	YES(3)	NO(2)	NO(1)	YES(1)	U(2)	S,B	
Toxaphene	U(2)	YES(1)	YES(2)	NO(2)	NO(1)	YES(1)	U(1)	S,B	
Polychlorinated Biphenyls	YES(2)	YES(1)	U(3)	U(3)	NO(3)	YES(1)	NO(1)	S,B	
2-Chloronaphthalene[f]	U(3)	U(3)	U(3)	U(2)	NO(3)	U(2)	YES(2)	S,B	
Halogenated Aliphatic Hydrocarbons									Konasewich[c] primary contaminants of concern: chlorinated ethylenes (ethenes), chlorinated butadienes.
Chloromethane	YES(2)	NO(3)	U(3)	NO(3)	NO(1)	NO(3)	NO(3)	W	
Dichloromethane	YES(2)	NO(2)	U(3)	NO(2)	NO(1)	NO(3)	NO(3)	W	
Trichloromethane	YES(2)	NO(2)	U(3)	NO(2)	NO(1)	NO(3)	NO(3)	W	
Tetrachloromethane	YES(2)	NO(2)	U(3)	NO(3)	NO(1)	U(2)	NO(3)	W	
Chloroethane	YES(2)	NO(2)	U(3)	NO(3)	NO(1)	NO(3)	NO(3)	W	
1,1-Dichloroethane	YES(2)	NO(3)	U(3)	NO(3)	NO(3)	NO(3)	NO(3)	W	
1,2-Dichloroethane	YES(2)	NO(3)	U(3)	NO(3)	NO(3)	NO(3)	U(2)	W	
1,1,1-Trichloroethane	YES(2)	NO(2)	U(3)	NO(2)	NO(3)	NO(3)	NO(3)	W	
1,1,2-Trichloroethane	YES(2)	NO(3)	U(3)	NO(2)	NO(3)	NO(3)	NO(3)	W	
1,1,2,2-Tetrachloroethane	U(2)	NO(3)	U(3)	NO(2)	NO(3)	U(3)	NO(3)	W	
Hexachloroethane	U(2)	U(3)	NO(3)	NO(3)	U(3)	U(3)	U(3)	W	
Chloroethene	YES(2)	NO(2)	NO(3)	NO(2)	U(3)	NO(2)	NO(2)	W	
1,1-Dichloroethene	YES(2)	NO(3)	U(3)	NO(3)	NO(3)	NO(3)	NO(3)	W	
1,2-trans-Dichloroethene	YES(2)	NO(3)	U(3)	NO(3)	NO(3)	NO(3)	NO(3)	W	
Trichloroethene	YES(2)	NO(2)	U(3)	NO(2)	NO(2)	U(2)	U(3)	W	
Tetrachloroethene	YES(2)	NO(2)	U(3)	NO(2)	NO(2)	U(2)	U(3)	W	
1,2-Dichloropropane	YES(3)	U(3)	U(3)	NO(3)	U(3)	U(3)	U(3)	W	
1,3-Dichloropropene	YES(2)	U(3)	U(3)	NO(3)	U(3)	NO(3)	U(3)	W	
Hexachlorobutadiene	U(2)	YES(2)	NO(3)	NO(3)	U(3)	YES(2)	U(3)	S,B	
Hexachlorocyclopentadiene	YES(3)	YES(3)	NO(3)	YES(2)	YES(1)	YES(2)	NO(2)	S,B	
Bromomethane	YES(3)	NO(3)	U(3)	NO(3)	YES(1)	NO(3)	NO(3)	W	
Bromodichloromethane	U(3)	U(3)	U(3)	U(3)	NO(1)	U(3)	U(3)	W,S	
Dibromochloromethane	U(3)	U(3)	U(3)	U(3)	NO(1)	U(3)	U(3)	W,S	
Tribromomethane	YES(3)	U(3)	U(3)	U(3)	NO(1)	U(3)	U(3)	W,S	
Dichlorodifluoromethane[f]	YES(3)	U(3)	U(3)	NO(3)	NO(2)	U(3)	U(3)	W,S	
Trichlorofluoromethane[f]	YES(3)	U(3)	U(3)	NO(3)	NO(2)	U(3)	U(3)	W,S	

APPENDIX E (Continued)

Chemical	Importance in Aquatic Transport[a]			Importance in Determining Aquatic Fate[a]				Initial Environmental Compartment for Sampling[b]	Primary Concerns Identified in Puget Sound at Present
	Volatilization	Sorption	Transport downstream	Photolysis/Oxidation	Hydrolysis	Bioaccumulation	Biotransformation/ Biodegradation		
Halogenated Ethers									
Bis(chloromethyl)ether[f]	NO(2)	NO(2)	NO(3)	NO(2)	YES(1)	NO(1)	NO(2)	W	
Bis(2-chloroethyl)ether	YES(3)	NO(3)	U(3)	NO(3)	NO(3)	NO(3)	NO(3)	W	
Bis(2-chloroisopropyl)ether	YES(3)	NO(3)	U(3)	NO(3)	U(3)	NO(3)	U(3)	W	
2-Chloroethyl vinyl ether	YES(3)	NO(3)	U(3)	NO(3)	U(1)	NO(3)	U(3)	W,S	
4-Chlorophenyl phenyl ether	U(2)	U(2)	U(3)	U(3)	NO(3)	U(1)	U(2)	S,B	
4-Bromophenyl phenyl ether	U(3)	U(3)	U(3)	U(3)	NO(3)	U(3)	U(3)	S,B	
Bis(2-chloroethoxy)methane	NO(2)	NO(2)	YES(3)	NO(2)	U(3)	NO(3)	U(3)	W	
Monocyclic Aromatics									Konasewich[c] primary contaminants of concern: hexachlorobenzene and other chlorinated benzenes, (polychlorinated dibenzofurans and their possible precursors tetrachlorophenol) and pentachlorophenol.
Benzene	YES(1)	U(3)	U(3)	NO(2)	NO(3)	NO(3)	U(2)	S	
Chlorobenzene	YES(2)	U(3)	U(3)	NO(3)	NO(3)	U(2)	U(2)	S,B	
1,2-Dichlorobenzene	YES(2)	U(3)	U(3)	NO(3)	NO(3)	U(2)	U(2)	S,B	
1,3-Dichlorobenzene	U(3)	U(3)	U(3)	NO(3)	NO(3)	YES(3)	U(3)	S,B	
1,4-Dichlorobenzene	U(3)	U(3)	U(3)	NO(3)	NO(3)	YES(3)	U(3)	S,B	
1,2,4-Trichlorobenzene	U(3)	U(3)	U(3)	NO(3)	NO(3)	YES(3)	U(3)	S,B	
Hexachlorobenzene	U(3)	YES(2)	U(3)	NO(3)	NO(3)	YES(1)	NO(3)	S,B	
Ethylbenzene	YES(2)	U(3)	U(3)	NO(3)	NO(3)	NO(3)	U(3)	S	
Nitrobenzene	U(3)	U(3)	U(3)	U(3)	NO(3)	NO(3)	U(3)	S	
Toluene	YES(2)	U(3)	U(3)	NO(3)	NO(3)	NO(3)	U(3)	S	
2,4-Dinitrotoluene	NO(3)	YES(2)	U(3)	YES(2)	NO(3)	U(3)	U(3)	S	
2,6-Dinitrotoluene	NO(3)	YES(2)	U(3)	YES(2)	NO(3)	U(3)	U(3)	S	
Phenol	U(2)	NO(2)	U(2)	YES(2)	NO(2)	NO(2)	YES(1)	S	
2-Chlorophenol	NO(3)	NO(3)	U(3)	U(3)	NO(3)	U(2)	U(3)	W	
2,4-Dichlorophenol	NO(3)	NO(3)	U(3)	NO(3)	NO(3)	U(3)	YES(2)	W	
2,4,6-Trichlorophenol	NO(3)	U(3)	U(3)	NO(3)	NO(3)	U(3)	U(3)	W	
Pentachlorophenol	NO(3)	YES(1)	YES(1)	YES(1)	NO(3)	YES(1)	YES(1)	S	
2-Nitrophenol	NO(2)	YES(2)	U(3)	YES(3)	U(3)	NO(3)	NO(1)	S,B	
4-Nitrophenol	NO(1)	YES(1)	U(3)	YES(3)	U(3)	NO(3)	NO(1)	S	
2,4-Dinitrophenol	NO(2)	YES(3)	U(3)	YES(3)	U(3)	NO(3)	U(2)	S	
2,4-Dimethyl phenol	NO(3)	U(3)	U(3)	YES(3)	NO(2)	U(3)	U(3)	S	
p-Chloro-m-cresol	NO(3)	NO(3)	U(3)	YES(3)	NO(3)	NO(3)	U(3)	S,B	
4,6-Dinitro-o-cresol	NO(3)	YES(3)	U(3)	YES(3)	NO(3)	U(3)	U(3)	S	

APPENDIX E (Continued)

Chemical	Importance in Aquatic Transport[a]			Importance in Determining Aquatic Fate[a]				Initial Environmental Compartment for Sampling[b]	Primary Concerns Identified in Puget Sound at Present
	Volatilization	Sorption	Transport downstream	Photolysis/Oxidation	Hydrolysis	Bioaccumulation	Biomagnification/ Biodegradation		
Phthalate Esters and Polycyclic Aromatic Hydrocarbons									
Phthalate Esters:									Konasewich[c] primary contaminants of concern: phthalate esters, naphthalene and substituted naphthalene benzo[a]anthracene and dibenzo[a]anthracene, fluoroanthenes, benzo[a]pyrene (and chlorinated and bromonaphthalenes).
Dimethyl	NO(3)	U(2)	YES(1)	NO(3)	U(2)	U(2)	U(2)	S,B	
Diethyl	NO(3)	U(2)	YES(1)	NO(3)	NO(3)	U(2)	U(2)	S,B	
Di-n-butyl	NO(3)	YES(1)	YES(1)	NO(3)	NO(3)	U(2)	U(2)	S,B	
Di-n-octyl	NO(3)	U(2)	U(2)	NO(3)	NO(3)	U(2)	U(2)	S,B	
Bis(2-ethylhexyl)	NO(3)	YES(1)	YES(1)	NO(3)	NO(3)	YES(1)	YES(1)	S,B	
Butyl benzyl	U(3)	U(3)	U(3)	NO(3)	NO(3)	U(2)	YES(3)	S,B	
Polycyclic Aromatic Hydrocarbons									
Acenaphthene	NO(3)	YES(3)	U(3)	YES(3)	NO(3)	NO(3)	YES(3)	S,B	
Acenaphthylene	NO(3)	YES(3)	U(3)	YES(3)	NO(3)	NO(3)	YES(3)	S,B	
Fluorene	NO(3)	YES(3)	U(3)	YES(3)	NO(3)	NO(3)	YES(3)	S,B	
Naphthalene	U(3)	U(3)	U(3)	YES(3)	NO(3)	NO(2)	YES(1)	S,B	
Anthracene	U(3)	YES(2)	U(3)	YES(3)	NO(3)	NO(2)	YES(1)	S,B	
Fluorathene	NO(3)	YES(2)	U(3)	YES(3)	NO(3)	NO(2)	YES(2)	S,B	
Phenanthrene	NO(3)	YES(2)	U(3)	YES(3)	NO(3)	NO(2)	YES(2)	S,B	
Benzo[a]anthracene	NO(3)	YES(2)	U(3)	YES(1)	NO(3)	NO(2)	YES(2)	S,B	
Benzo[b]fluoranthene	U(3)	YES(2)	U(3)	YES(3)	NO(3)	NO(3)	YES(2)	S,B	
Benzo[k]fluoranthene	U(3)	YES(2)	U(3)	YES(3)	NO(3)	NO(3)	YES(3)	S,B	
Chrysene	U(3)	YES(2)	U(3)	YES(3)	NO(3)	NO(3)	YES(3)	S,B	
Pyrene	U(3)	YES(2)	U(3)	YES(3)	NO(3)	NO(3)	YES(3)	S,B	
Benzo[ghi]perylene	U(3)	YES(1)	U(3)	U(3)	NO(3)	U(3)	U(3)	S,B	
Benzo[a]pyrene	U(3)	YES(3)	U(3)	YES(1)	NO(3)	U(3)	YES(1)	S,B	
Dibenzo[a]anthracene	U(3)	YES(3)	U(3)	U(3)	NO(3)	U(3)	U(3)	S,B	
Indeno[1,2,3-cd]pyrene	U(3)			U(3)	NO(3)	U(3)	U(3)	S,B	
Nitrosamines and Misc. Compounds									
Dimethyl nitrosamine	NO(3)	NO(3)	U(3)	YES(2)	NO(3)	NO(3)	NO(2)	W	
Diphenyl nitrosamine	NO(3)	U(3)	U(3)	U(3)	NO(3)	U(3)	U(3)	S,B	
Di-n-propyl nitrosamine	NO(3)	NO(3)	U(3)	YES(2)	NO(3)	NO(3)	NO(2)	W,S,B	
Benzidine	NO(1)	YES(1)	U(3)	YES(1)	NO(2)	NO(2)	U(2)	S	
3,3'-Dichlorobenzidine	NO(1)	YES(1)	U(3)	YES(1)	NO(3)	YES(1)	NO(1)	S,B	
1,2-Diphenylhydrazine	NO(1)	YES(2)	U(3)	U(2)	NO(2)	YES(3)	U(3)	S,B	
Acrylonitrile	YES(2)	NO(3)	U(3)	NO(3)	NO(3)	NO(3)	U(3)	W,S	

KEY: a. From Callahan et al. 1979. For each chemical and related process, two ratings are presented. The first is a statement of importance: YES, NO, or U (uncertain). The second numerical rating deals with available supporting data, explained below:
(1) Quantitative (rate constants, half-lives) data are available to support conclusions.
(2) Qualitative description only; there are no direct environmental data. However, some laboratory data can be extrapolated to support conclusions.
(3) There are no supporting data available; evidence is drawn from theoretical calculations, estimates, results for similar chemicals, and inferences.

b. From Chapman et al. 1982. W = water; S = sediments; B = biota.

c. Konasewich et al. 1982. (Other contaminants may be considered of more concern as more information becomes available.)

d. Dexter et al. 1981.

e. Crecelius pers. comm.

f. No longer on priority pollutant listing.